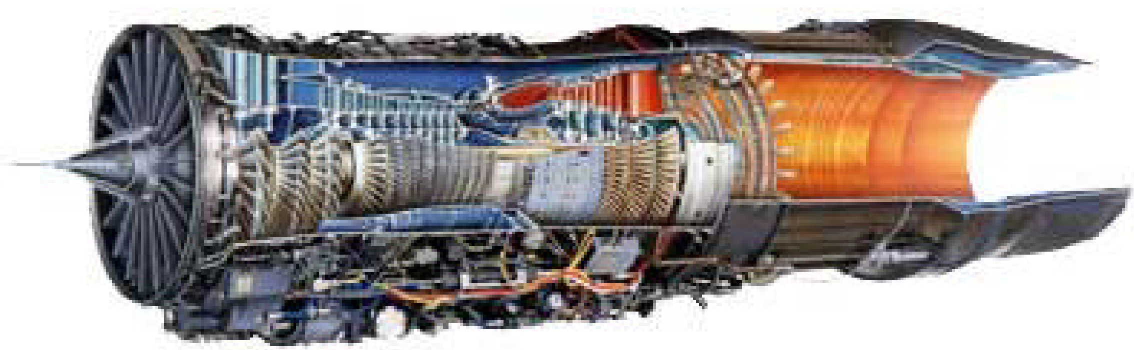
ESTCP
Cost and Performance Report

(PP-0023)



Replacement of Chromium Electroplating on Gas Turbine Engine Components Using Thermal Spray Coatings

May 2006

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Replacement of Chromium Electroplating on Gas Turbine Engine Components Using Thermal Spray Coatings**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**59**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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TO: Director, Freedom of Information & Security Review, Rm. 2C757, Pentagon

1. DOCUMENT DESCRIPTION

a. TYPE Cost & Performance Report	b. TITLE Replacement of Chromium Electroplating on Gas Turbine Engine Components Using Thermal Spray Coatings (PP-0023)
c. PAGE COUNT 55	d. SUBJECT AREA Environmental Security Technology Certification Program

2. AUTHOR/SPEAKER

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d. OFFICE Naval Research Laboratory		e. AGENCY Naval Research Laboratory

3. PRESENTATION/PUBLICATION DATA *(Date, Place, Event)*

Posting on the ESTCP web site.

CLEARED
For Open Publication

AUG 2 5 2005 6

Office of Security Review
Department of Defense

4. POINT OF CONTACT

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e. OFFICE OUSD(I&E)	f. AGENCY OUSD (A&T)
g. SIGNATURE	h. DATE SIGNED *(YYYYMMDD)* 20050615

DD FORM 1910, MAR 1998 (EG) PREVIOUS EDITION MAY BE USED. WHS/DIOR, Mar 98

Posted 11/20

05 C-1749

COST & PERFORMANCE REPORT
ESTCP Project: PP-0023

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ACRONYMS AND ABBREVIATIONS

ALC	Air Logistics Center
AMS	Aerospace Materials Specification
AMT	advanced mission test
ANG	Air National Guard
ANSI	American National Standards Institute
APS	air plasma spray
ASTM	American Society for Testing and Materials
CBA	cost/benefit analysis
cermet	ceramic/metal
CFR	Code of Federal Regulations
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOE	design of experiment
ECAM	Environmental Cost Analysis Methodology
EFH	equivalent flight hours
EHC	electrolytic hard chrome
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FPI	fluorescent penetrant inspection
GEAE	GE Aircraft Engines
GTE	gas turbine engine
HCAT	Hard Chrome Alternatives Team
HCF	high-cycle fatigue
hex-Cr	hexavalent chromium
HVOF	high-velocity oxygen-fuel
IARC	International Agency for Research on Cancer
IRR	internal rate-of-return
JG-PP	Joint Group on Pollution Prevention
JTP	Joint Test Protocol
JTR	Joint Test Report
LCF	low-cycle fatigue
NADEP	Naval Air Depot
NADEP-CP	Naval Air Depot Cherry Point

ACRONYMS AND ABBREVIATIONS (continued)

NADEP-JAX	Naval Air Depot Jacksonville
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NPV	net present value
OC-ALC	Oklahoma City Air Logistics Center
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
P&W	Pratt & Whitney
PEL	permissible exposure limit
PEWG	Propulsion Environmental Working Group
PVD	physical vapor deposition
rpm	rotations per minute
SAE	Society of Automotive and Aerospace Engineers
scfh	standard cubic feet per hour
SOR	source of repair
T-400	Tribaloy 400
T-800	Tribaloy 800
TWA	time-weighted average
UHS	ultra-high sensitivity
WC/CO	tungsten carbide/cobalt

ACKNOWLEDGEMENTS

The financial and programmatic support of the Environmental Security Technology Certification Program, under the direction of Dr. Jeffrey Marqusee, Director, and Mr. Charles Pellerin, Program Manager for Pollution Prevention, is gratefully acknowledged. The financial and programmatic support of the Propulsion Environmental Working Group is also gratefully acknowledged.

The authors would also like to express thanks to the following individuals who made substantial contributions to the execution of the project:

- Mr. Robert Bondaruk and Mr. Charles Alford, U.S. Air Force Aeronautical Systems Center (Propulsion Environmental Working Group)
- Mr. Johnny Tsiao and Mr. Jeff Marnix, Oklahoma City Air Logistics Center
- Mr. Jerry Schell, GE Aircraft Engines
- Mr. Gary Shubert, Pratt & Whitney
- Mr. John Sauer, Sauer Engineering
- Mr. Phil Bretz, Metcut Research, Inc.
- Mr. Richard Vanderstraten, Hitemco, Inc.
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1.0 EXECUTIVE SUMMARY

Background: Electrolytic hard chrome (EHC) plating is a technique that has been in commercial production for more than 50 years. It is a critical process used for applying hard coatings to a variety of aircraft components in manufacturing operations and for general re-build of worn or corroded components that have been removed from aircraft during overhaul. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr) being a known carcinogen. During operation, chrome plating tanks emit a hex-Cr mist into the air, that must be ducted away and removed by scrubbers. Wastes generated from plating operations must be disposed of as hazardous waste, and plating operations must abide by U.S. Environmental Protection Agency (EPA) emissions standards and Occupational Safety and Health Administration (OSHA) permissible exposure limits (PEL). Recent studies have clearly shown that there are a significant number of excess deaths at the current PEL of 100 $\mu g/m^3$. OSHA is currently under court order to establish a new hex-Cr PEL by January 2006, and the metal finishing industry expects it to be in the range of 1 $\mu g/m^3$. A Navy/Industry task group concluded that the cost of compliance for all Navy operations that utilize hex-Cr (i.e., not just plating) would be in excess of $10 million if the PEL was reduced to less than 5 $\mu g/m^3$.

Previous research and development efforts had established that high-velocity oxygen-fuel (HVOF) thermal spray coatings are the leading candidates for replacing hard chrome. HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (cermet) such as tungsten carbide/cobalt (WC/Co) coatings that are dense and highly adherent to the base material. They also can be applied to thicknesses in the same range as that used for EHC. Currently, there are HVOF thermal spray systems commercially available. Although there are a wide number of applications for these coatings, their qualification as an acceptable replacement for hard chrome plating has not been adequately demonstrated, particularly for fatigue-sensitive aircraft and engine components. The Hard Chrome Alternatives Team (HCAT) was formed to perform the demonstration/validation for the HVOF coatings.

Objectives of the Demonstration: The objectives were to demonstrate through materials and component testing that the performance of several HVOF and plasma spray coatings on gas turbine engine (GTE) components was equal or superior to that of EHC coatings. Materials testing included axial fatigue, fretting wear, salt-fog corrosion, and carbon seal wear.

Regulatory Drivers: EHC plating operations must comply with 40 Code of Federal Regulations (CFR) Part 63 (National Emissions Standards for Hazardous Air Pollutants) and 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards). The workplace environment must comply with an OSHA PEL of 100 $\mu g/m^3$ for hex-Cr. As stated above, it is anticipated that the hex-Cr PEL will be significantly reduced. In the Netherlands, there is pending legislation to reduce allowable hex-Cr exposure to 1.5 $\mu g/m^3$, and the U.K.'s Ministry of Defense is proposing an even stricter standard of 0.5 $\mu g/m^3$. If OSHA adopts a new PEL in this range, then the costs associated with EHC plating will significantly increase, and it is possible that EHC operations will have to shut down at many Department of Defense (DoD) facilities.

Demonstration Results:

- Fatigue: Low-cycle fatigue tests under strain control and high-cycle fatigue tests under load control were conducted at 300ºF and 750ºF on IN-718, A-286, AMS-355, 9310, IN-901, 4340 and 17-4PH alloy specimens coated with EHC, HVOF WC/17Co, Tribaloy 400, Tribaloy 800 and Cr_3C_2/NiCr, and plasma spray Tribaloy 400 to thicknesses of 0.003 or 0.015 in. Cycles-to-failure at different levels of maximum stress or strain were measured. In general, the average number of cycles-to-failure at any stress or strain level for the thermal-spray-coated specimens was equal to or greater than for EHC-coated specimens except for IN-718 and 17-4PH substrates, where approximately half of the specimens showed fatigue performance inferior to EHC.

- Wear: Fretting wear tests were conducted at 300ºF and 750ºF for 4340 blocks coated with EHC, HVOF WC/17Co, Tribaloy 800 and Cr_3C_2/NiCr, and plasma spray Tribaloy 400 to a thickness of 0.003 in sliding against M50, IN-718, IN-901, or 17-4PH. For tests conducted at 750ºF, HVOF WC/Co coatings performed significantly better than EHC and the other thermal spray coatings when sliding against all of the mating materials, except IN-718 where the coating performance was equivalent to EHC. For tests conducted at 300ºF, the results were less definitive but, in the majority of cases, WC/Co performance was equivalent or superior to EHC, with the performance of the other thermal spray coatings generally below that of EHC.

- Corrosion: ASTM B117 salt fog exposure tests were conducted on 4340 rod and plate specimens and IN-718 rod specimens coated with EHC, HVOF Tribaloy 400, Tribaloy 800 and Cr_3C_2/NiCr, and plasma spray Tribaloy 400 to thicknesses of 0.003 or 0.015 in. After 1,000 hours exposure, the average appearance ratings for the 0.003 in-thick thermal spray coatings were lower than for the EHC coatings on 4340. The average appearance ratings for the 0.015 in-thick thermal spray coatings were equivalent to the EHC coatings. Very little corrosion was observed on any coatings on the IN-718 substrates.

- Carbon Seal Wear: Tests consisted of the rotational sliding of shafts coated with EHC, HVOF WC/17Co, Tribaloy 400, Tribaloy 800 and Cr_3C_2/NiCr, and plasma spray Tribaloy 400 to a thickness of approximately 0.004 in against two different grades of carbon seals. In general, the performance of the HVOF WC/Co coatings was equivalent to EHC in terms of both the wear of the coating and the mating carbon seal material whereas the performance of the other thermal spray coatings was inferior to the EHC coatings.

- Component Testing: An advanced mission test (AMT) was conducted on a TF33 engine in which seven components that are normally coated with EHC were coated with HVOF WC/17Co. Oil analysis conducted during the test and analysis of oil filters conducted subsequent to the test indicated virtually no degradation of the WC/Co coatings. Inspection of the coatings subsequent to the test indicated performance superior to what would be expected for EHC. The components will be installed in another AMT engine for additional testing to assess ultimate life.

- Cost Assessment: A detailed cost/benefit analysis was conducted using the Environmental Cost Analysis Methodology (ECAM) at a military gas turbine engine overhaul facility that processes more than 1,000 components per year. For a constant throughput of components, the analysis showed an annual cost avoidance of approximately $50,000. For a declining throughput based on improved component performance, there was a 15-year net present value of $362,000. If all hard chrome plating could be eliminated from the depot, then the 15-year net present value was more than $1.1 million. If a new proposed hexavalent chromium permissible exposure limit of 1 microgram-per-cubic-meter is implemented, then the 15-year net present value for the constant-throughput, declining-throughput and chrome-elimination cases would increase to $350,000, $700,000, and $2.9 million, respectively.

Stakeholder/End-User Issues: The success of the materials testing and the TF33 AMT has resulted in the Air Force proceeding with implementation of HVOF coatings on that and other gas turbine engines through the Component Improvement Program, with the ultimate goal of eliminating hard chrome plating on all components for which thermal spray is amenable (i.e., where line-of-sight is not an issue). This includes repair of the F100, F101, F110, F118, and T56 engines. Naval Air Depot Jacksonville has implemented HVOF coatings on the TF34 engine and is exploring the qualification of the coatings on other engine components.

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2.0 TECHNOLOGY DESCRIPTION

The replacement of hard chrome plating in aircraft manufacturing activities and maintenance depots is a high priority for the DoD. Hard chrome plating is a technique used in commercial production for more than 50 years and is a critical process used for applying hard coatings to a variety of aircraft components in manufacturing operations and for general rebuilding of worn or corroded components that have been removed from aircraft during overhaul. In particular, chrome plating is used extensively on GTE components such as shafts and bearing journals. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hex-Cr being a known carcinogen having a level of toxicity greater than arsenic or cadmium. During operation, chrome plating tanks emit a hex-Cr mist into the air, which must be ducted away and removed by scrubbers. Wastes generated from plating operations must be disposed of as hazardous waste, and plating operations must abide by EPA emissions standards and OSHA PELs.

A significant lowering of the hex-Cr PEL would most likely have the greatest cost impact on military and commercial repair facilities. Such a change has been expected since the mid 1990s, but OSHA did not begin the process of issuing a new PEL until 2004. OSHA was responding to a lawsuit filed in 2002 by a citizens group and union that petitioned OSHA to issue a lower PEL and a subsequent ruling by a federal district court upholding the petition. The court ruling required OSHA to publish a new draft hex-Cr PEL in the Federal Register no later than October 2004, conduct public review and hearings in 2005, and issue a final rule in January 2006. The metal finishing industry is anticipating that the final PEL will be in the range of 1 $\mu g/m^3$ with a 0.5 $\mu g/m^3$ action level, which would represent a two-order-of-magnitude reduction from the current PEL of 100 $\mu g/m^3$. The expected compliance costs in all industries including electroplating, welding, painting, and chromate production is $226 million.

In anticipation of the change, in 1995 a Navy/Industry task group [1] under the coordination of the Naval Sea Systems Command (NAVSEA) studied the technical and economic impact of a reduction in the hex-Cr PEL. At the time, a reduction in the 8-hour time-weighted average (TWA) from the existing 100 $\mu g/m^3$ to 0.5 to 5.0 $\mu g/m^3$ was being considered. The Navy/Industry task group performed the following tasks:

- Identified the manufacturing and repair operations, materials, and processes used in Navy ships, aircrafts, other weapons systems, and facilities where worker exposure to hex-Cr would be expected
- Developed data on current worker exposure levels to hex-Cr using OSHA Method 215
- Estimated the technical and economic impact of the anticipated reductions in hex-Cr exposure on Navy ships, aircrafts, other weapons systems, and facilities
- Identified future actions required to comply with the anticipated PEL reductions.

The following operations within the Navy were identified as having the potential for exposing workers to hex-Cr:

- Metal cleaning (including abrasive blasting and grinding) of chromate-coated materials
- Electroplating of chromium
- Painting and application of chromate paints and coatings
- Welding, thermal spraying, and thermal cutting.

The following conclusions were reached by the task group:

- Regulated areas for hex-Cr would have to be created in much greater numbers than have been required for cadmium or lead exposure.

- Local exhaust ventilation, which is the presently available engineering control, is not completely effective in reducing exposure to below 0.5 $\mu g/m^3$ for many operations or even below 5 $\mu g/m^3$ in some cases.

- The inability of engineering controls to consistently reduce worker exposure below the anticipated PEL levels will significantly increase the use of respirators.

- The costs of reducing the hex-Cr PEL will include costs for training, exposure monitoring, medical surveillance, engineering controls, personal protective equipment, regulated areas, hygiene facilities, housekeeping and maintenance of equipment. There will also be costs due to reduced efficiency of the operations involving hex-Cr as well as adjacent operations and personnel.

- The estimated costs for compliance with a PEL of 0.5 $\mu g/m^3$ at Navy facilities include an initial, one-time cost of approximately $22,000,000 and annual costs of approximately $46,000,000 per year.

- The estimated costs for compliance with a PEL of 5.0 $\mu g/m^3$ at Navy facilities include an initial, one-time cost of approximately $3,000,000 and annual costs of approximately $5,000,000 per year.

- In addition to the greatly increased cost that would be associated with chrome plating, turnaround times for processing components would be significantly increased as well, impacting mission readiness.

Based on the projections of the metal finishing industry and the study conducted by NAVSEA in 1995, it is clear that a reduction of the hex-Cr PEL to a range near 1 $\mu g/m^3$ will greatly increase the cost and processing times associated with hard chrome plating within DoD.

Previous research and development efforts [2, 3] had established that HVOF thermal spray coatings are the leading candidates for replacement of hard chrome. Using commercially available thermal spray systems, HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (e.g., WC/Co) coatings that are dense and highly adherent to the base material. They also can be applied to thicknesses in the same range as that currently being used for chrome plating.

To conduct the advanced development work required for qualification of the HVOF coatings, the Tri-Service Dem/Val of Chromium Electroplating Replacements project was established in

March 1996, sponsored principally by the Environmental Security Technology Certification Program (ESTCP). A project team, designated the Hard Chrome Alternatives Team (HCAT), was formed to execute the project. From 1996 to early 1998, the HCAT acquired and installed HVOF thermal spray systems at the Naval Aviation Depot in Cherry Point, North Carolina, and the Corpus Christi Army Depot. It also performed some generic fatigue and corrosion testing on HVOF WC/17Co and Tribaloy 400 coatings compared to EHC coatings. In general, the performance of the HVOF coatings was superior to that of the EHC coatings.

While these studies were valuable, it was realized in early 1998 that, because hard chrome plating was being used on such a wide variety of aircraft components, it would be impossible to develop one test plan or conduct one series of tests that would address all materials and component qualification requirements. It was therefore decided to develop separate projects related to categories of aircraft components onto which hard chrome was being used. At the same time, the DoD Joint Group on Pollution Prevention (JG-PP) decided to partner with the HCAT on developing and executing the various projects. JG-PP is chartered by the Joint Logistics Commanders to coordinate joint service pollution prevention activities during the acquisition and sustainment of weapons systems. HCAT and JG-PP determined that the first projects executed would be on landing gear and propeller hubs, with projects on hydraulic actuators and helicopter dynamic components to come later. The landing gear and propeller hub projects have now been completed with extensive materials testing generally showing that HVOF coatings such as WC/17Co demonstrate performance superior in fatigue, wear, and corrosion to EHC coatings. Rig and flight tests on WC/17Co-coated components showed acceptable performance for the HVOF coatings and, in many cases, superior performance to what would be expected had the components been coated with EHC. As a result of these projects, HVOF is being implemented at many Air Force and Navy repair facilities for processing landing gear and propeller hub components.

The Propulsion Environmental Working Group (PEWG) was founded in the late 1980s to address environmental issues impacting the DoD propulsion community and the military gas turbine engine industry. They have executed a number of demonstration/validation projects related to qualifying new, environmentally friendly technologies associated with aircraft and land-based gas turbine engines. In the summer of 1999, the PEWG and HCAT partnered to present a proposal to ESTCP for qualifying thermal spray coatings as a hard chrome replacement on GTE components. The project was approved and initiated in February 2000.

An analysis was first conducted of the extent of hard chrome plating within the propulsion community. Table 1 lists the DoD gas turbine engines onto which hard chrome is currently applied to at least one component (delineated according to the DoD aviation depot where the overhaul of the engine takes place). It indicates the manufacturer, the aircraft utilizing the engine, and the number of parts identified on that engine that have hard chrome applied either by the manufacturer or in overhaul.

Table 1. Summary of Gas Turbine Engines, Categorized by Depot Where Engine is Overhauled, Original Equipment Manufacturer (OEM), End-Use Aircraft, and Number of Parts onto Which Hard Chrome is Applied.

Depot	Engine TMS	OEM	End Use	# Parts
Naval Air Depot (NADEP) Cherry Point	T58	GE Aircraft Engines (GEAE)	CH-46 Helicopter (Navy and Marines)	29
	T64	GEAE	CH-53 Helicopter (Navy and USAF)	27
	T-400	Pratt & Whitney (P&W) Canada	UH-1N (Marines)	6
	F402	Rolls Royce United Kingdom (RR UK)	AV-8B (Marines)	3
NADEP North Island	LM2500 (TF39 Core)	GEAE	Military Marine (U.S. Navy and 23 International Navies)	22
NADEP Jacksonville	TF34	GEAE	S-3 (Navy); A-10 (Air Force)	29
	F404	GEAE	F/A-18 (Navy); F-117 (Air Force)	5
	J52	P & W	A-4; A-6; EA-6B	6
Oklahoma City Air Logistics Center (ALC)	TF33- P3/P103	P & W	B-52H (Air Force)	12
	TF33-P7A	P & W	C-141 (Air Force)	
	TF33-P100	P & W	E-3 (Air Force)	
	TF33-P102A/B	P & W	KC-135; C-18; E-8 (AF)	
	F100	P & W	F-15, F-16 (Air Force)	41
	F118	GEAE	B-2 (Air Force)	3
	F110-100/129	GEAE	F-16 (Air Force)	
	F110-400	GEAE	F-14 (Navy)	
San Antonio ALC	T56	RR Allison	C-130	42
Corpus Christi Army Depot	T700	GEAE	H-60, AH-64, SH-2 Helicopters	10
TOTAL				**235**

Subsequent to conducting this analysis, the stakeholders decided that a Joint Test Protocol (JTP) would be developed to cover only the materials testing related to all engines. This document was produced through meetings and electronic communication involving all stakeholders and delineated all the materials testing required to qualify thermal spray coatings as a hard chrome plating replacement. In conjunction with the materials testing, it was decided that each DoD service and GTE manufacturer would evaluate the hardware under consideration for thermal spray coating and decide if additional component or engine testing beyond the materials JTP would be necessary. Such additional testing could be required due to the critical nature of the mechanical system response for some specific GTE components. A demonstration plan was developed for the TF33 engine, and an AMT was conducted in which seven components that are normally coated with EHC were instead coated with HVOF WC/17Co.

3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Technology background and theory of operation: HVOF is a standard commercial thermal spray process in which a powder of the material to be sprayed is injected into a supersonic flame of a fuel (usually hydrogen, propylene, or kerosene), as shown in Figure 1. The powder particles are accelerated to high speed and soften in the flame, forming a dense, well-adhered coating on the substrate. The coating material is usually a metal or alloy (such as Tribaloy or stainless steel), or a cermet (such as cobalt cemented tungsten carbide, WC/Co). The technology is used to deposit coatings about 0.003 in-thick on OEM parts and to rebuild worn components by depositing layers up to 0.015 in-thick.

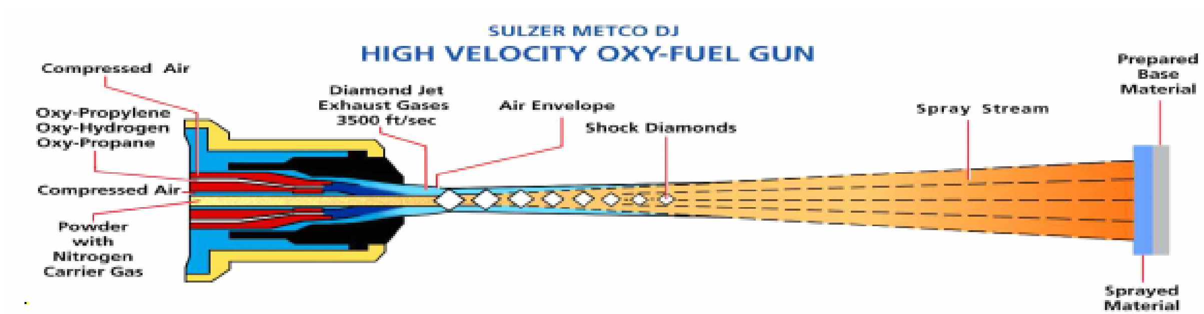

Figure 1. Schematic of HVOF Gun and Process (Sulzer Metco DiamondJet).

Applicability: HVOF thermal spraying was originally developed primarily for GTE applications. The primary thermal spray processes are Flame Spray, Plasma Spray, Arc Spray, HVOF and the recently developed cold spray. The original high-velocity spray technology was the pulsed deposition detonation gun (D-gun) developed by Union Carbide (later Praxair). The quality of the wear-and erosion-resistant spray coatings produced by this method was much better than the lower speed methods, and continuous flame HVOF was developed as a competitive response.

The original applications for HVOF were wear components in GTEs, such as shafts and bearing journals. As the availability and use of the technology grew, it began to be applied to a wide range of other types of coatings and applications, including aircraft components such as flap and slat tracks, landing gear, and hydraulics for commercial aircraft. It is now being used in many applications outside the aircraft industry, such as industrial rolls and vehicle hydraulics. The original aircraft wear applications, primarily used by Boeing, were for otherwise intractable spot problems that neither the original alloy nor chrome plate could solve.

The technology can be used to spray a wide variety of alloys and cermets. It is limited for high temperature materials such as oxides, most of which cannot be melted in the flame. The areas to be coated must be accessible to the gun — i.e., they must be line-of-sight.

Material to be replaced: HVOF coatings are used to replace hard chrome plate (especially using carbide cermets and high temperature oxidation-resistant Tribaloys). The combination of HVOF NiAl with an overlayer carbide is also used to replace the combination sulfamate Ni/hard chrome. HVOF coatings can also be used to replace some hard Ni and electroless Ni coatings on such components as flap tracks and propeller hubs. In the HCAT program, the primary application is hard chrome replacement.

3.2 PROCESS DESCRIPTION

Installation and operation: The HVOF gun can be handheld and used in an open-fronted booth. However, the supersonic gas stream is extremely loud and requires that the operator use very effective ear protection. For this reason the unit is usually installed on a six-axis robot arm in a soundproof booth, programmed, and operated remotely. Most depots already use this type of booth for their existing plasma spray operations. Since the method is frequently used for cylindrical items, the most common arrangement is to rotate the component on a horizontal rotating table and move the gun up and down the axis. Figure 2 shows an example of application of an HVOF coating to a landing gear inner cylinder. A similar set-up would be used for application of HVOF coatings to components such as shafts from gas turbine engines.

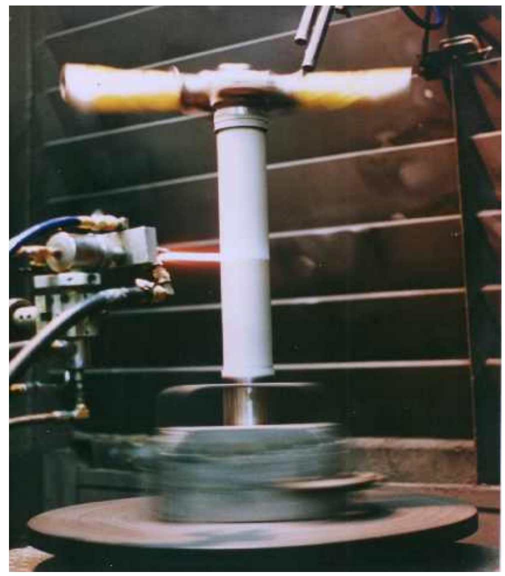

Figure 2. HVOF Spray of Landing Gear Inner Cylinder

Facility design: The installation requires:

- *A soundproof booth*. Booths are typically 15 ft square, with a separate operator control room, an observation window, and a high volume air handling system drawing air and dust out of the booth through a louvered opening (shown in Figure 2).
- *Gun and control panel*. The gun burns the fuel and oxygen inside its combustion chamber and injects the powder axially into the flame. The gas exits the gun at supersonic speed, while the particles are accelerated to high velocity but usually remain subsonic. The control panel controls the gas flows, cooling water, etc.
- *Powder feeder*. Powder is typically about 60 μm in diameter and is held in a powder feeder, which meters the powder to the gun at a steady rate, carried on a gas stream. Two powder feeders are commonly used to permit changeover from one coating to another without interrupting the spraying.
- *Six-axis industrial robot and controller*. Most installations use an industrial robot to manipulate the gun and ensure even spraying. The robot is often suspended from above to leave the maximum possible floor space for large items.

- *Supply of oxygen*. This is frequently a bulk storage container outside the building. Alternatively, bottled gas can be used, but because of the high usage rate of up to 2,000 standard cubic feet per hour (scfh), even a standard 12-bottle setup lasts only a few hours in production.

- *Supply of fuel gas or kerosene (bottled or bulk)*. Hydrogen is the most common fuel, supplied in bulk or in bottles. Praxair TAFA guns use kerosene, which is significantly cheaper and less dangerous.

- *Dust extractor and bag-house filter system*. The air extracted from the booth is laden with overspray, particles that have failed to stick to the surface (often 20-50% of the total sprayed). The air is blown into a standard bag house, often located outside the building, where the dust is removed.

- *Dry, oil-free compressed air for cooling the component and gun*. Air cooling prevents the components being overheated (temperatures must be kept below about 400°F for most high strength steels).

- *Water cooling for gun*. Not all guns are water cooled, but most are.

The facility must be capable of supplying the necessary gas pressures and flows. Standard commercial equipment currently in service already meets these requirements. Equipment vendors are able to supply turnkey systems.

Performance: HVOF spray guns deliver about 4-5 kg per hour of powder material, of which 65% typically enters the coating, for a coating rate of about 3 kg/hour. For a common 0.010 in WC/Co rebuild coating (which will be sprayed to a thickness of 0.013-0.015 in), an HVOF gun can deposit about 900 in^2/hr. This permits application of a 0.010 in-thick coating onto the outer surface of a cylinder that is 2 ft long with a 4 in diameter in about 30 minutes, compared with about 10-15 hours for chrome plating.

Specifications: The following specifications and standards apply to HVOF coatings:

- Prior to the HCAT program, the only aerospace specifications were those issued by prime contractors such as Boeing, whose BAC 5851 thermal spray specification, supported by BMS 10-67G powder specification, is still one of the most quoted standards.

- Aerospace Materials Specification (AMS) 2447 was developed with the assistance of the HCAT team and issued by the Society of Automotive and Aerospace Engineers (SAE) in 1998. It is now a widely used standard in the aerospace industry.

- In order to provide specifications for spraying and grinding selected HVOF coatings at depots and vendors, HCAT has worked through SAE to promulgate several standards:

  - AMS 7881, a powder specification for WC/Co, and AMS 7882, a powder specification for WC/CoCr, were both issued in April 2003.

  - AMS 2448, a specification describing procedures for spraying WC/Co and WC/CoCr coatings using HVOF, was issued in August 2004.

- AMS 2449, a specification describing procedures for low-stress grinding of HVOF WC/Co and WC/CoCr coatings, was issued in August 2004.

Training: Just as plating shops typically have several personnel who handle masking, racking, demasking, etc., it is common for HVOF shops to have three or four technicians dedicated to masking and spraying. HVOF training is essential and is usually provided by equipment vendors such as Praxair and Sulzer Metco. Training is also available through the Thermal Spray Society. Depot personnel taking part in the HCAT program have been trained by Jerry Schell, a thermal spray coatings expert at GE Aircraft Engines. Since thermal spray is a more complex technology than electroplating, plating line personnel cannot be transferred successfully to an HVOF shop without extensive retraining.

Health and safety: The process does not produce air emissions or toxic wastes. Co powder is an International Agency for Research on Cancer (IARC) Group 2B material, which means that "The agent (mixture) is possibly carcinogenic to humans," whereas Cr^{6+} is an IARC Group 1 material, "Known to be carcinogenic to humans." However, the OSHA PEL for Co (8hr TWA) of 0.1 mg(Co)/m^3, is lower than the 1 mg(Cr)/m^3 for metallic chrome, and is the same as the 0.1 mg(Cr)/m^3 for Cr^{6+}. Unlike chrome plating, the Co is not emitted into the air. Excess Co-containing powder is drawn from the spray booth and captured in the bag house. Nevertheless, personnel should wear a dust respirator when handling the powder, working in the booth, or grinding the coating. While the powders are usually about 60 μm in diameter, they can break apart on impact, producing 10 μm or smaller particles. The American Welding Society recommends the use of a respirator complying with American National Standards Institute (ANSI) Z88.2.

Ease of operation: Since in commercial systems the entire system is programmable, including the gun control and robot, it is generally easy to operate. The operator must create masking (usually shim stock shadow masks) and must develop the correct spray parameters and gun motions. While vendors supply standard operating conditions for different materials, these may have to be optimized experimentally for new materials and powders, and must be adjusted for different components to ensure proper coating speed and gun traverse rate. Small diameter components, for example, must be rotated faster than large ones to maintain the same deposition rate and coating structure. In this respect, operating an HVOF system is considerably more complex than electroplating.

3.3 PREVIOUS TESTING OF THE TECHNOLOGY

Prior to the HCAT program, HVOF technology had been successfully used for years by Boeing for their commercial aircraft and by General Electric Aircraft Engines for GTEs. In the period 1993-1996, Keith Legg, Bruce Sartwell, GEAE, Cummins Diesel, and Corpus Christi Army Depot carried out an evaluation of chrome alternatives funded by the Defense Advanced Research Projects Agency (DARPA). The program evaluated HVOF, physical vapor deposition (PVD), and laser cladding and concluded that HVOF was the best overall alternative for use in depots and most OEM aircraft applications [3]. At the beginning of the HCAT program, Lufthansa successfully completed flight tests of HVOF coatings on commercial landing gear and Delta began conducting similar flight tests.

3.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Replacing hard chrome plating is a great deal more complex than simply putting down a hard coating. The alternative must not only work technically, but it must fit with the entire life cycle of use and maintenance, and it must be a reasonable, mature technology for depot use. The advantages and limitations of HVOF are summarized in Table 2.

Table 2. Advantages and Limitations of HVOF as a Chrome Replacement.

Advantages/Strengths	Disadvantages/Limitations
Technical	
Higher hardness, better wear resistance, longer overhaul cycle, less frequent replacement	Brittle, low strain-to-failure—can spall at high load (an issue primarily for carrier-based aircraft)
Better fatigue, corrosion, embrittlement	Line-of-sight, cannot coat IDs
Material can be adjusted to match service requirements	More complex than electroplating, requires careful quality control
Depot and OEM fit	
Most depots already have thermal spray expertise and equipment	WC-Co requires diamond grinding wheel. Only HVOF alloys can be plunge ground.
Can coat large areas quickly	
Can be chemically stripped	
Many commercial vendors	
Environmental	
No air emissions from plating tank, no high volume rinse water	Co toxicity
No requirement for use of perchloroethylene as a post-plating cleaner as with hard chrome	

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4.0 DEMONSTRATION DESIGN

4.1 PERFORMANCE OBJECTIVES

Performance objectives established for this project consisted of both materials testing performed on coupons manufactured from the same base materials from which hard-chrome-plated GTE components are fabricated and an AMT for the TF33 GTE. The objectives were established by the following stakeholders in the project:

- Air Force Aeronautical Systems Center
- Air Force Propulsion Single Item Manager
- Oklahoma City Air Logistics Center (OC-ALC)
- Naval Air Systems Command (NAVAIR)
- Naval Air Depot Jacksonville (NADEP-JAX)
- Naval Air Depot Cherry Point (NADEP-CP)
- GE Aircraft Engines (GEAE) (OEM)
- Pratt & Whitney (P&W) (OEM)
- Rolls-Royce/Allison (OEM)

Coordination of the project was provided by the Naval Research Laboratory and Rowan Technology Group.

As discussed in Section 2.0, an analysis was first conducted of the components from the various DoD GTEs onto which hard chrome is currently applied, with the results of that analysis shown in Table 1. Most of the components could be grouped by function in a few families, which included shafts, housings, gears, and seals. Then the stakeholders analyzed the types of conditions under which the EHC-coated components were subjected (e.g., cyclic stresses, sliding wear, and corrosion). From these analyses, the materials testing requirements were established. A stakeholders meeting was held in October 2000 to discuss the testing requirements and create an outline of a JTP. A first draft of the JTP was produced by Jerry Schell from GEAE and was distributed to the stakeholders. Many revisions were generated through additional meetings and electronic correspondence, with a final version [4] approved by the stakeholders in September 2001. The specific types of materials testing delineated in the JTP were fatigue, wear (both sliding wear and carbon seal wear), and corrosion. A detailed description of these tests can be found later in this section. The performance objectives, also called acceptance criteria, were as follows:

- *Fatigue.* Cycles-to-failure at different stress or strain levels were measured for fatigue specimens coated with either EHC or a thermal spray coating. These data were plotted with stress/strain on the vertical axis and cycles-to-failure on the horizontal axis and smooth curves were fit to the data points. If the curves for the thermal spray coatings fell on or above those for the EHC, then the thermal spray coatings were considered to have passed the acceptance criteria.

- *Wear.* Fretting wear tests were conducted for specimens coated with EHC and various thermal spray coatings with different materials as the mating surfaces. If the average wear volume for the thermal spray coatings was equal to or less than for EHC coatings, then the thermal spray coatings were considered to have passed the acceptance criteria.

- *Corrosion.* American Society for Testing and Materials (ASTM) B117 salt-fog exposure tests were conducted on specimens coated with EHC and various thermal spray coatings. Protection ratings were determined in accordance with ASTM specifications. If the average ratings for the thermal spray coatings were greater than or equal to those for EHC, then the thermal spray coatings were considered to have passed the acceptance criteria.

- *Carbon seal testing.* Tests consisting of the rotational sliding of EHC- or thermal-spray-coated shafts against two different grades of carbon seals were conducted. If the average wear volume for the carbon seals and thermal spray mating coatings was equal to or less than the wear volume for the carbon seals and EHC mating coatings, then the thermal spray coatings were considered to have passed the acceptance criteria.

The TF33 was selected for the component test because it is a widely used legacy engine and the schedule for the AMT was amenable to the project. The acceptance criteria for the AMT were that the HVOF WC/Co coatings did not show any evidence of delamination, cracking, or extensive wear and that the overall performance was superior to that expected for EHC-coated components in the same test.

4.2 SELECTION OF TEST FACILITY

The OC-ALC was the lead demonstration overhaul facility and NADEP-JAX the secondary. At the beginning of the project, both depots already had operational HVOF systems, although the one at OC-ALC required significant upgrading before it would be production-ready. This upgrading took place during the execution of the project, and the system was ready for production coating of GTE components by the summer of 2004.

4.3 TEST FACILITY HISTORY/CHARACTERISTICS

In 1942, Tinker Field was established near Oklahoma City, and its industrial plant repaired B17 and B24 bombers and engines, and fitted B29s for combat. In 1946, Tinker expanded to include the Douglas Aircraft Plant and was named Oklahoma City Air Materiel Area. In the 1950s, it expanded to include overhaul of the B52 bomber and the KC135 tanker. In 1974, the depot was renamed the Oklahoma City Air Logistics Center (OC-ALC).

The ALC industrial complex has 55 buildings with 5.5 million square ft, and plant equipment valued at more than $500 million. The maintenance work force is 6,100, and the payroll more than $300 million. The center manages approximately 82,000 accessory items and annually repairs approximately 250,000 exchangeable components.

OC-ALC manages 19 types of engines (aircraft jet engines, missile engines, and helicopter engines). It is designated the source of repair (SOR) for 11 of the 19 and is currently repairing the TF30, TF33, F101, F108, F110, and F118 engines. The center also is the SOR for the Navy F110-400 and TF30-414A engines and manages the J79 engine. Within the Air Force, there are approximately 18,500 active engines and in FY 2004, OC-ALC expects to overhaul 975 engines.

During overhaul many components must be repaired due to wear, gouges, or corrosion pits. For items that can be repaired, EHC plating is often used subsequent to machining of the damaged area. As examples, on the TF33 engine there are 12 separate components and 41 on the F100 that are commonly plated with hard chrome. In FY 2002, there were approximately 700 TF33 components onto which EHC was applied during repair operations. Approximately 70% of the total GTE hard chrome plating workload at OC-ALC is for TF33 components, so the replacement of EHC on that engine would provide the greatest benefit.

4.4 PHYSICAL SET-UP AND OPERATION

OC-ALC currently has one fully operational Sulzer-Metco DJ2700 HVOF thermal spray system and is currently installing a second system. Figure 3 shows the spray booth that is 16 ft wide by 12 ft deep by 10 ft high. Even the largest GTE components that are currently EHC plated can be mounted in it. Figure 4 shows the spray gun mounted to a Fanuc M16i robot with air jets used for cooling components during coating application. The system also consists of a Sulzer Metco Diamond Jet Controller and a 9MP Powder Feeder. The instantaneous surface temperature of components is measured using an infrared pyrometer, as shown in Figure 5.

Figure 3. Thermal Spray Booth at OC-ALC.

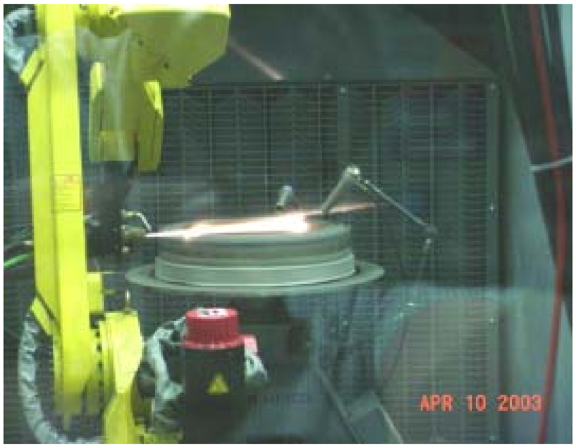

Figure 4. Sulzer-Metco DJ2700 Spray Gun (in operation) **Mounted to Fanuc M16i Robot Inside Spray Booth at OC-ALC** (also shows air jet nozzles for cooling components during spraying).

Figure 5. Infrared Pyrometer for Measuring Surface Temperature of Components During Coating Application.

4.5 SUBSTRATE MATERIAL SELECTION

This project differed from the previous HCAT projects in that a GTE is a complete mechanical system that consists of a wide variety of components with different design considerations, operating conditions, and parent materials. The other HCAT projects focused on a specific family of components such as landing gear and propeller hubs that have similar design considerations and operating conditions, and they are fabricated from relatively few parent materials. The survey of the 235 different GTE components listed in Table 1 that are currently coated with EHC included a determination of the alloy from which each component was fabricated. These alloys are listed in Table 3. It obviously was not possible to conduct materials tests for thermal spray and EHC coatings on all these 18 alloys, but seven alloys, as indicated in Table 4, were selected for testing based on volume of use, as generic alloy family representatives, and for special considerations such as low tempering temperatures (e.g., 9310 steel) or very complex multi step heat-plus-cryogenic treatments (e.g., AM355). All materials were tested in an appropriate heat treat condition, as defined in Table 5. The GTE components represented by these alloys may have varied heat treat conditions depending on the engine and component, so heat treatments representative of the most demanding applications were selected.

4.6 COATING SELECTION AND PARAMETER OPTIMIZATION

This project differed from the previous two HCAT projects by the number of different thermal spray coatings (both HVOF and air plasma spray [APS]) considered as potential alternatives to EHC. There were several considerations taken into account in determining which coatings would be evaluated. One was the potential lower cost and greater availability of APS coatings at depots. A second was because of the difficulty of stripping HVOF coatings (which generally involves an electrolytic process), because one GTE OEM preferred not to expose any rotating

Table 3. Alloys Used to Fabricate GTE Components onto Which EHC Plating is Applied.

IN-718	4140	17-4PH
IN-901	4340	410 SS
Inco W	8630	L605
AM-355	8740	C-355
A-286	9310	
Greek Ascolloy	17-22H	
	Nitralloy 135	
	Lapelloy C	

Table 4. Alloys Selected for Testing and Their Compositions.

Selection		Composition in Weight (%)											
Alloy	**AMS Spec**	**Ni (+Co)**	**Cr**	**Fe**	**Mo**	**Nb+ Ta**	**Ti**	**Al**	**C**	**Mn**	**Cu**	**Si**	**B, other**
IN-718	5663	50-55	19.0	19.0	3.0	5.1	0.9	0.50	0.08	0.35 max	0.75 max	0.45 max	0.006 max
IN-901	5660 5661	41-44	13.5	35.0	6.0	----	2.7	0.25	0.05	----	----	----	0.01
AM-355	5743	4.5	15.5	75.5	2.9	----	----	-----	0.13	0.85	----	0.5	0.1 Nit
A-286	5731	26.0	15.0	52.7	1.3	----	2.1	0.3	0.04	1.5	----	0.7	0.005, 0.3 V
17-4PH	5355	4.1	16.0	76.4	----	0.28	----	----	----	-----	3.2	----	----
4340	6415	1.75	0.8	95.8	0.25	----	----	----	0.40	0.70	----	0.3	----
9310	6260 6265	3.25	1.2	94.1	0.12	----	----	----	0.10	0.55	0.35 max	0.3	----

Table 5. Heat Treatment Parameters for Alloys Selected for Testing.

Material	Heat Treat
IN-718	C50TF37, CL-B
IN-901	AMS 5660
A-286	C50TF20, CL-A
AM-355	C50TF53, CL-A or B
4340	MIL-H-6875 (HRc 48-50)
9310	C50TF50-S8 (HRc 37-38)
17-4PH	AMS 5604 (H1000 temper)

GTE components to an electrolytic process. APS coatings can generally be removed using nonelectrolytic processes such as high-pressure water jet.

The coatings selected for testing are summarized in Table 6, which also indicates the powder used for coating application. Note that one of the coatings has the designation Tribaloy 400 (T-400) and another the designation Tribaloy 800 (T-800).

Table 6. Coatings Selected for Testing.

HVOF Process		PS Process	
Composition, Wgt %	**Powder**	**Composition, Wgt %**	**Powder**
WC/17Co	Diamalloy 2005	Co-28 Mo-8 Cr-2 Si**	Metco 66F-NS
Cr_3C_2-20 (Ni,Cr)	Amdry 5260/Diam 3007		
Co-28 Mo-17 Cr-3 Si*	Diamalloy 3001		
Co-28 Mo-8 Cr-2 Si**	Diamalloy 3002		

* T-800
** T-400

As in all coating methods, the properties and performance of the coating depend on both the coating material and the deposition conditions. Optimal coating properties can therefore be obtained only when the critical deposition parameters are in the proper range. In chrome plating, the coating properties are primarily governed by solution chemistry, temperature, and current density. HVOF and APS spraying are more complex to optimize since there are many more variables in the deposition process. For this reason, the thermal spray coatings were optimized in the HCAT program by either a full or limited design of experiment (DOE) approach, which permits optimum conditions to be identified from a limited set of test runs, obviating the need for a full test matrix that would entail many hundreds of deposition tests.

In order to optimize a coating, it is important to decide at the outset what property, or set of properties, is to be optimized. This is especially true for thermal spray coatings, where it has been found, for example, that a coating optimized for minimum wear can demonstrate relatively poor fatigue properties. Within the HCAT program, the fatigue-critical nature of applications on components such as in gas turbine engines was quickly identified as the major life-limiting characteristic. This did not eliminate the need to evaluate other properties such as corrosion and wear, but coating optimization initially concentrated on fatigue performance. Optimization of the process was carried out for three important reasons:

- To define a thermal spray process that would achieve the desired performance and property goals
- To establish manufacturing robustness and the process window for a reliable process
- To understand the process and trends that give an indication of and can later be used as a trouble-shooting guide; when parameters are identified as significant, these variables will be the first areas of investigation in problem solving.

Although the goal of the DOE studies was the optimization of fatigue performance, there are only a certain number of measurements that can be used for quality control of the process when a coating is sprayed.

- Microstructure (primarily measurement of porosity, unmelted particles, and oxides)
- Hardness (macro and micro)
- Residual stress in the coating as indicated by the curvature of an Almen strip subsequent to coating deposition (compressive residual stress is always desired)
- Substrate temperature during coating application
- Deposition rate.

These measurements have proved to be adequate for the purpose of quality control defining the coating. Since the deposition process is known to be uniform and stable if operating parameters are kept constant, the above measurements can be made on test samples set up to see the same deposition conditions as the components to be coated.

Since a full DOE (not published) had previously been performed on the HVOF WC/17Co [5] and T-400 coatings, the same optimized coating parameters were used for the GTE test coupons. A limited DOE was performed on the other two HVOF coatings and the APS T-400 coatings. For all the HVOF coatings, hydrogen was used as the fuel gas. Deposition parameters that were measured and optimized for HVOF included powder size, distance from gun nozzle to substrate, feed gas ratio (fuel-to-oxygen), and thickness of coating per pass. Deposition parameters that were measured and optimized for APS included powder size, distance from gun nozzle to substrate, argon gas flow, and thickness of coating per pass. All of the optimized deposition parameters used on the materials test coupons are presented in the GTE Joint Test Report (JTR) [6].

4.7 ANALYTICAL METHODS

The materials testing requirements and acceptance criteria were delineated in the Materials JTP [4] and will only be summarized here.

4.7.1 Fatigue

Fatigue is a very critical property for many gas turbine engine components; consequently, there is an extensive amount of fatigue data on alloys that are used in GTEs. When coatings are applied to the alloys, the evaluation of fatigue essentially is the analysis of how the application of the coating affects the fatigue strength of the alloy, i.e., a comparison is made between the cycles-to-failure at selected stress/strain values for coated and uncoated specimens. It is generally recognized that, when EHC is applied to most alloys used in gas turbine engines, the fatigue strength will be reduced because there are microcracks and residual tensile stresses in the coatings.

Although plasma spray processes have seen widespread use in the aerospace industry for many years, they have tended to be limited to non-fatigue-critical applications, largely due to the heat input of the process and tensile coating stresses. The commercial development of the HVOF process, which relies more on kinetic than thermal energy for final coating properties and permits compressive coating stress, has started to move the design community towards thermal spray in fatigue-driven components. Since fatigue performance is driven by material strength and is especially related to near-surface effects, fatigue-critical applications require careful definition and control of the thermal spray process such that (1) the coatings are deposited in a state of residual compressive stress which will tend to reduce crack propagation and thus minimize any fatigue debit associated with the coating application and (2) deposition of the coatings is performed with a minimum of surface heating so as to prevent a loss of mechanical properties.

The need for low-cycle-fatigue (LCF) testing in GTE applications is driven by design consideration for the number of engine take-off/landing cycles. During this time period, engine parts experience the most severe loading environment of very high constant strain and can exhibit failure in a low number of cycles. In this type of control mode, the load will actually drop as the specimen begins to fail to maintain the constant strain condition. An extensometer is used during testing to ensure that constant strain is maintained. The need for high-cycle-fatigue (HCF) testing in GTE applications, in conjunction with the LCF studies, is driven by components which experience a high number of cycles during extended flight times. With HCF, the critical element is not strain but a constant load—thus, the term “load control.” In contrast to strain control, an extensometer is not used and the load is the same through the test and into the failure regime. For this project, it was decided to conduct both LCF testing under strain control and HCF testing under load control.

Both strain- and load-control fatigue tests were conducted in accordance with ASTM E466-96 and standard plots of either maximum stress or strain versus cycles-to-failure were generated. Specimens were fabricated from the alloys indicated in Table 4 and were heat treated in accordance with the specifications in Table 5. The specimens were in the smooth-gage configuration as shown in Figure 6, meaning there was a constant 0.25-in gage diameter over a gage length of 0.75 in.

Prior to coating application, most of the specimens were shot-peened, then all were grit-blasted. EHC coatings were applied to some of the specimens in accordance with QQ-C-320 to thicknesses of 0.006 or 0.018 in and then were ground to final thicknesses of 0.003 or 0.015 in with an Ra surface finish of 16 microinches. The thermal spray coatings were deposited using the parameters as specified in the JTR [6] to thicknesses of 0.006 or 0.018 in, then ground to final thicknesses of 0.003 or 0.015 in with an Ra surface finish of 8 microinches. In all cases, the coating was applied as a 0.5-in-wide patch on the specimen, as indicated in Figure 6. The grinding of the coatings followed the procedures specified in AMS 2449 and discussed in Section 3.2. Even with low-stress grinding techniques applied, it is still possible that the grinding could introduce additional stresses into the coating. In service, almost all HVOF coatings will be ground; therefore, it was important to use the same grinding techniques as would be used on actual components so the fatigue data would be representative of those situations.

Fatigue tests were conducted in air at a temperature of either 300ºF or 750ºF. The control modes were as follows:

- *Low-cycle fatigue.* Strain control, A ratio of 0.95 (equivalent to R ratio of 0.026), frequency of 0.5-5.0 Hz, triangular input strain waveform
- *High-cycle fatigue.* Load control, A ratio of 0.5 (equivalent to R ratio of 0.33), frequency of 5-59 Hz, sine wave load input signal
- *Number of specimens.* Ten uncoated baseline per alloy, six coated per alloy/coating combination, minimum of three stress/strain levels per group.

The two temperatures selected for testing reflected the range of temperatures encountered by EHC-coated components in gas turbine engines. A total of 988 separate fatigue tests were performed.

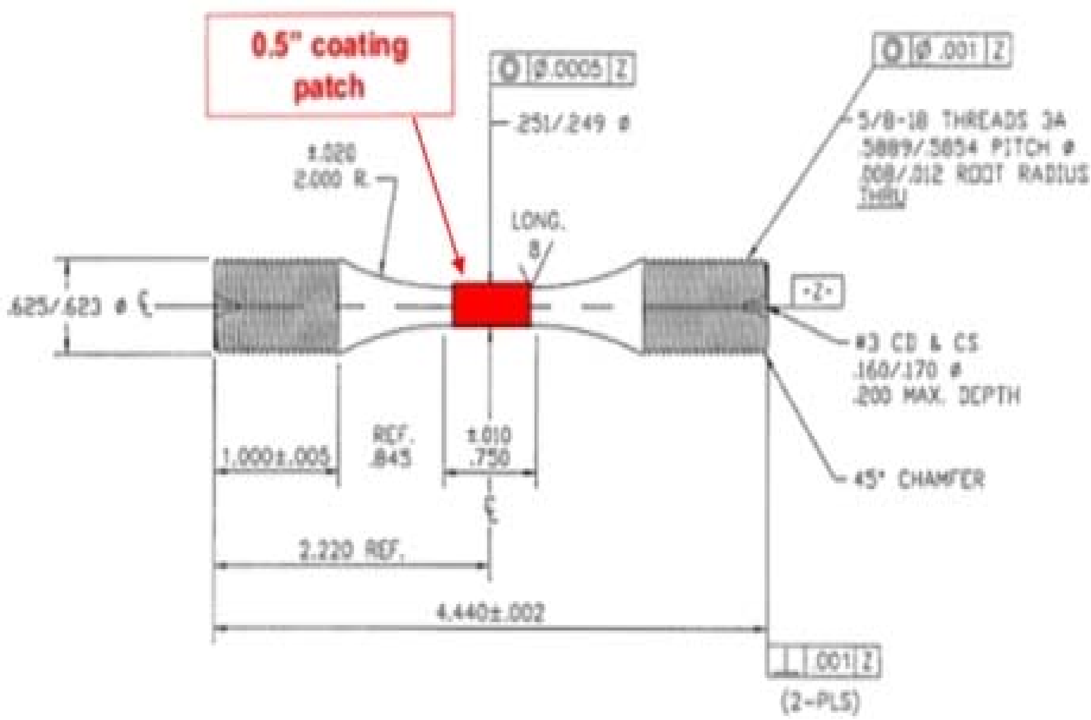

Figure 6. Schematic of Smooth-Gage Fatigue Specimen Showing Location of Coating Patch.

4.7.2 Wear

A fretting wear test was selected to simulate the dithering or vibration movement between two mating components that are typical in GTEs. The test configuration is shown in Figure 7. The coating to be evaluated is applied to one face of a metal block. A metal shoe with a small contact area is placed against the coated block with a uniform load applied. The block is then oscillated in a direction perpendicular to the applied load with a short stroke and fairly high frequency.

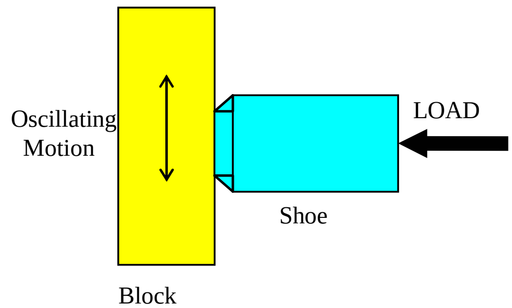

Figure 7. Cross-Sectional Schematic of Fretting Wear Test Configuration.

Virtually all the blocks used in the wear tests were fabricated from 4340 steel. The coatings that were applied to the blocks were EHC, HVOF WC/17Co, HVOF Cr_3C_2/NiCr, HVOF T-800, and APS T-400. Surface preparation (i.e., shot peening and grit blasting) and coating deposition parameters were the same as those used for the fatigue specimens. The mating alloys (shoes) consisted of IN-718, IN-901, 17-4PH, and M50. Table 7 provides the wear test parameters. The contact area of the shoe on the block was 0.0675 square inches (0.06 in x 1.125 in); therefore, the contact stress was 53.3 ksi.

Table 7. Wear Test Parameters

Parameter	Value
Load	3,600 lbs
Duration	25,000 cycles (12,500 cycles for IN-901 shoes)
Frequency	4 Hz
Stroke (total length of travel per cycle)	.060 in
Temperature	300º/750ºF
Lubrication	Dry

The wear depth (i.e., amount of material removed) was measured at the completion of each test.

4.7.3 Corrosion

The substrate materials onto which the coatings were applied were 4340 steel and IN-718. For 4340, two different specimen geometries were used for the corrosion studies—rod and plate. For IN-718, only rods were used. The rods were 1 inch diameter and 6 inches long. The plates were 3x4x0.25 inches thick. Surface preparation and coating deposition parameters were the same as for the fatigue specimens. The coatings that were evaluated included EHC, HVOF T-400, HVOF T-800, HVOF Cr_3C_2/NiCr, and APS T-400. For some of the EHC coatings, a sulfamate nickel underlayer was applied to a minimum thickness of 0.0015 in, in accordance with QQ-N-290. For the plates, coatings

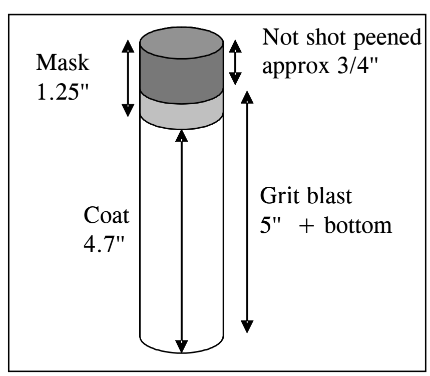

Figure 8. Schematic of Rod Corrosion Specimen.

were applied to one face, with the edges and reverse side coated with an inert epoxy. The area on the rods that was coated is indicated in Figure 8. The inert epoxy was applied to each end such that it extended just onto the coating. All coatings were applied to thicknesses of 0.006 or 0.018 in and were then ground to final thicknesses of 0.003 or 0.015 in.

ASTM B117 salt fog tests were conducted in a Q-Fog Model CCT600 salt spray chamber. The salt fog test is an accelerated corrosion test by which samples exposed to the same condition can be compared, thereby providing a means of ranking the relative corrosion resistance. For these tests, the mounting of the plate specimens in the chamber followed the B117 protocol. Since rod-shaped specimens are not in the B117 protocol, specimen holders (made from an inert material such as Teflon) the rods were placed in the holders with 4.25 in of the specimen exending out from the holder. The holders were constructed such that the rods sat at an angle of 45º to the vertical. As specified in the B117 protocol, the samples were exposed to a salt fog generated from a 5% sodium chloride solution with a pH between 6.5 and 7.2. The temperature in the chamber was maintained at 35ºC. Samples for each coating/substrate combination were placed in the salt fog chamber for a total exposure time of 1,000 hours. After removal from the salt fog chamber, the specimens were cleaned with a Scotch 3M abrasive pad to remove loosely adherent corrosion products. Then a protection rating was assigned to the specimen in accordance with ASTM B537.

4.7.4 Carbon Seal Testing

Carbon seal wear tests were performed due to their unique requirements. Carbon seals operate at the engine rotations per minute (rpm) and therefore have very high sliding speeds. There are two basic configurations for carbon seals, as shown in Figure 9. One is a face seal where the coating is applied to the flat face of the rotor, which rotates at a constant rpm and slides against a fixed stator onto which the carbon seal material is attached. The other is a radial seal where the coating is applied to the circumference of the rotor. A face seal configuration was used in these tests, whereby a spring assembly behind the stator provided a reasonably constant load against the rotor. The load was measured prior to initiating each test. The coatings that were evaluated included EHC, HVOF WC/17Co, HVOF Cr_3C_2/NiCr, HVOF T-400, HVOF T-800, and APS T-400. Surface preparation and coating deposition parameters were the same as those used for the fatigue specimens. Coatings were deposited to thicknesses of approximately 0.006 in then ground to final thicknesses ranging from 0.003 to 0.004 in. The coatings were ground to Ra surface finishes of either 4 or 8 microinches. Two grades of carbon seal material were evaluated, Graphitar 39 which has a Shore hardness value of 100 and Graphitar 67 which has a shore hardness value of 87. These two grades essentially cover the ranges of hardness for carbon seals. Tests were performed for a total of 48 hours with rotor rotational speeds of either 7,000 or 13,500 rpm. At the completion of each test, the amount of wear on the carbon seals and the coatings was measured using a profilometer.

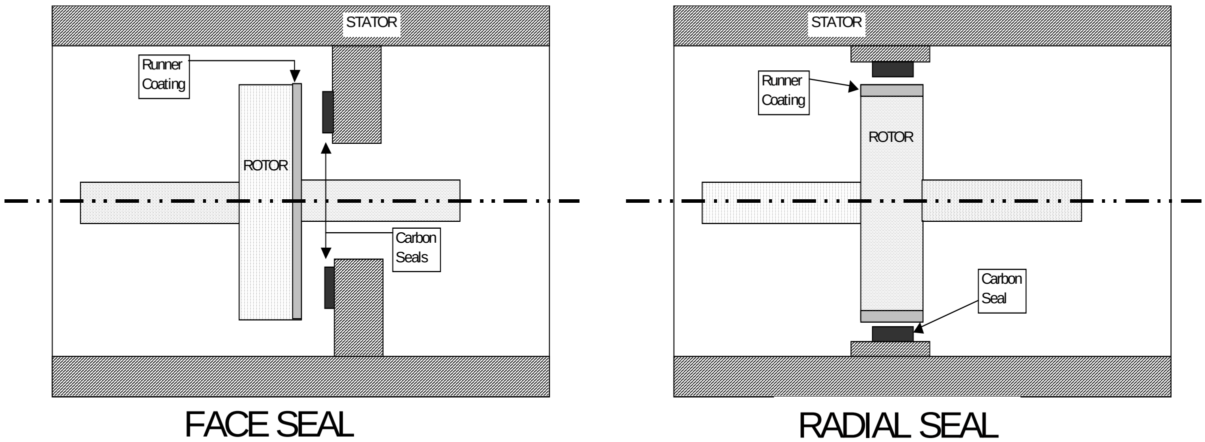

Figure 9. Schematic Drawings of Two Configurations for Carbon Seals.

5.0 PERFORMANCE ASSESSMENT

5.1 PERFORMANCE CRITERIA

The performance criteria for all the materials and component testing were described in Section 4.1. For all materials testing, the essential criterion was that the performance of specimens coated with the thermal spray coatings was equivalent or superior to the performance of identical specimens coated with EHC.

5.2 PERFORMANCE DATA

All of the performance data for the materials testing is presented in detail in the Joint Test Report [6]. Only selective data and summaries are presented here. For a more detailed discussion, refer to the Final Report for this project [7].

5.2.1 Materials Testing—Fatigue

The fatigue testing examined the performance of specimens fabricated from the alloys listed in Table 4 and coated with EHC compared to specimens coated with the thermal spray coatings listed in Table 6. As indicated in Section 4.7.1, both LCF (strain control) and HCF (load control) testing was conducted for final (ground) coating thicknesses of 0.003 in or 0.015 in and at temperatures of 300ºF or 750ºF. Fatigue performance was assessed through plots of cycles-to-failure as a function of the maximum stress or strain to which the specimens were subjected. For all tests, the fatigue performance of the thermal-spray-coated specimens was equivalent to or exceeded that of the EHC-coated specimens with the exception of some of the IN-718 and 17-4PH specimens. Figure 10 shows the data for LCF testing at 300ºF of 0.015-in-thick coatings on A-286 alloy specimens. For any given maximum level of strain, the cycles-to-failure are greater for the thermal spray coatings than for the EHC-coated specimens. Figure 11 shows the data for LCF testing at 300ºF of 0.015-in-thick coatings on 9310 alloy. As with the A-286 alloy, the fatigue performance of the thermal-spray-coated specimens exceeded that of the EHC-coated specimens.

On the other hand, Figure 12 shows the data for HCF testing at 300ºF of 0.015 in-thick coatings on IN-718 alloy where the fatigue performance of the thermal-spray-coated specimens was generally inferior to that of the EHC-coated specimens. Approximately half the data points (primarily at 750°F) for the carbide coatings on IN-718 were below those for EHC on IN-718 at equivalent stress or strain levels. The only other substrate where a significant number of data points fell below the EHC baseline was 17-4PH where almost 40% of the data taken at 750ºF for the thermal spray coatings was below that for EHC.

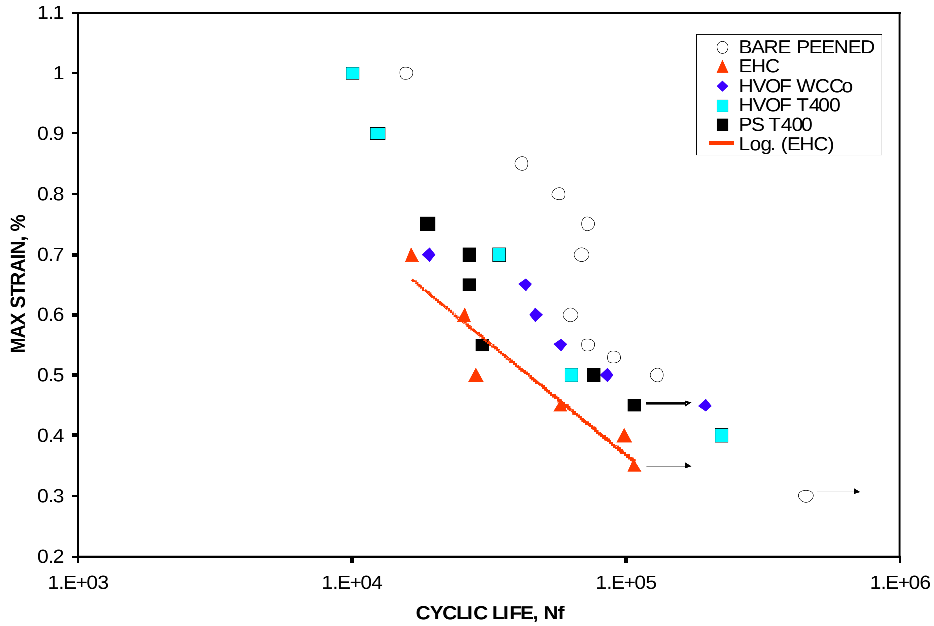

Figure 10. Cycles-to-Failure at Maximum Values of Strain for LCF Testing at 300ºF of Various 0.015 in-Thick Coatings Deposited on A-286 Alloy Specimens.

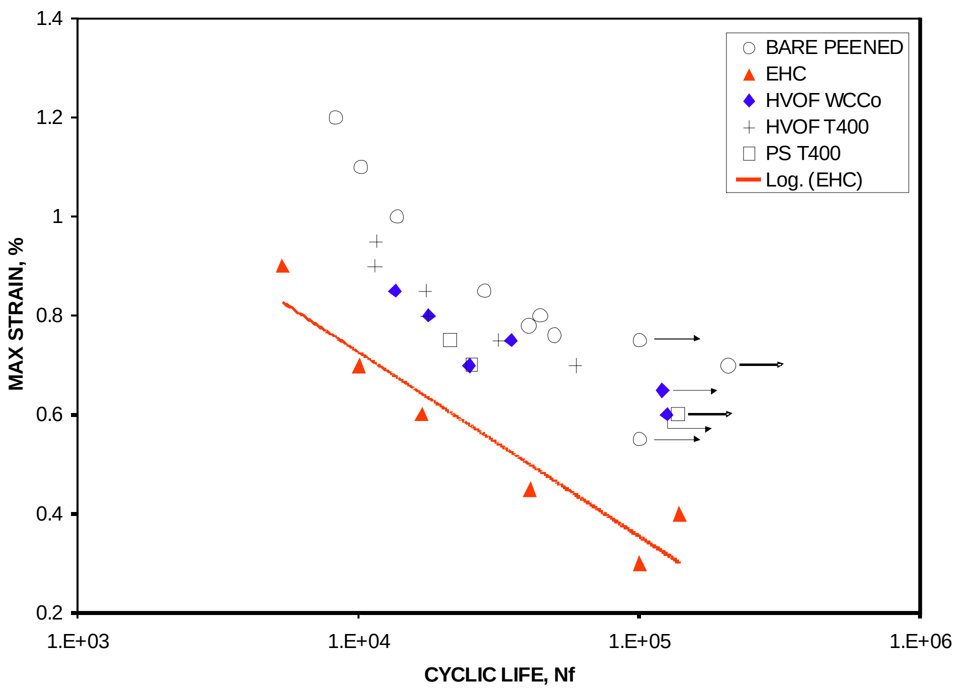

Figure 11. Cycles-to-Failure at Maximum Values of Strain for LCF Testing at 300ºF of Various 0.015 in-Thick Coatings Deposited on 9310 Alloy Specimens.

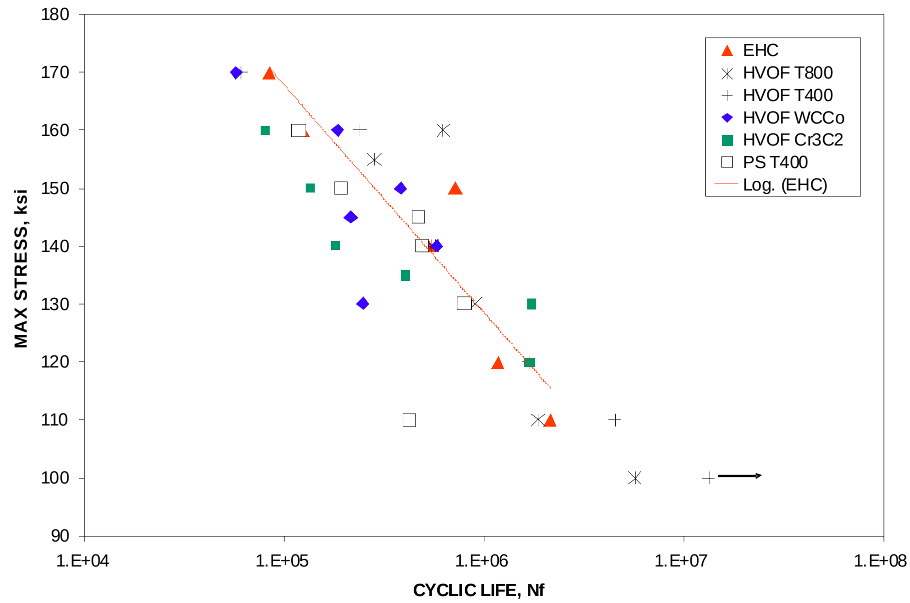

Figure 12. Cycles-to-Failure at Maximum Values of Stress for HCF Testing at 300ºF of Various 0.015-in-Thick Coatings Deposited on IN-718 Alloy Specimens.

5.2.2 Materials Testing—Wear

Figure 13 and Figure 14 show the wear coefficients (plotted as average wear depth) for the coated blocks and shoes, respectively, for testing done at 300ºF. In general, two tests were run for each coating/shoe combination at each temperature, but in those cases where the results were very disparate, three tests were run and are shown with cross-hatched bars in the figures.

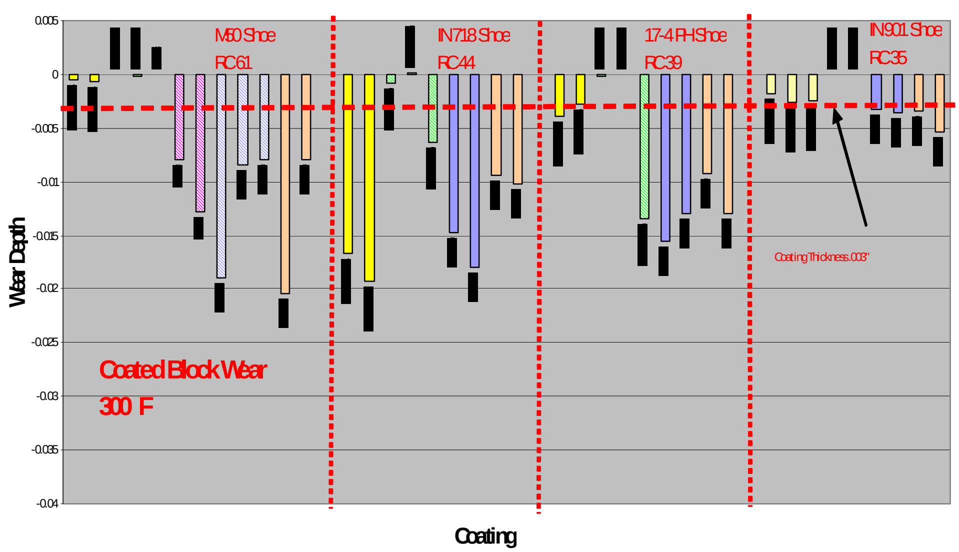

Figure 13. Wear Coefficients (plotted as average wear depth) **for Coated Blocks Against the Four Different Shoe Materials for Testing at 300ºF.**

The data is arranged in material hardness order from the M-50 to IN-901 shoes, with the Rockwell C hardness values indicated at the top of each set of data. Note that in Figure 13 the thickness of the coating is shown by a dashed line at a wear depth of 0.003 in. Thus, many of the wear tests were run beyond the point at which the coating had been completely removed.

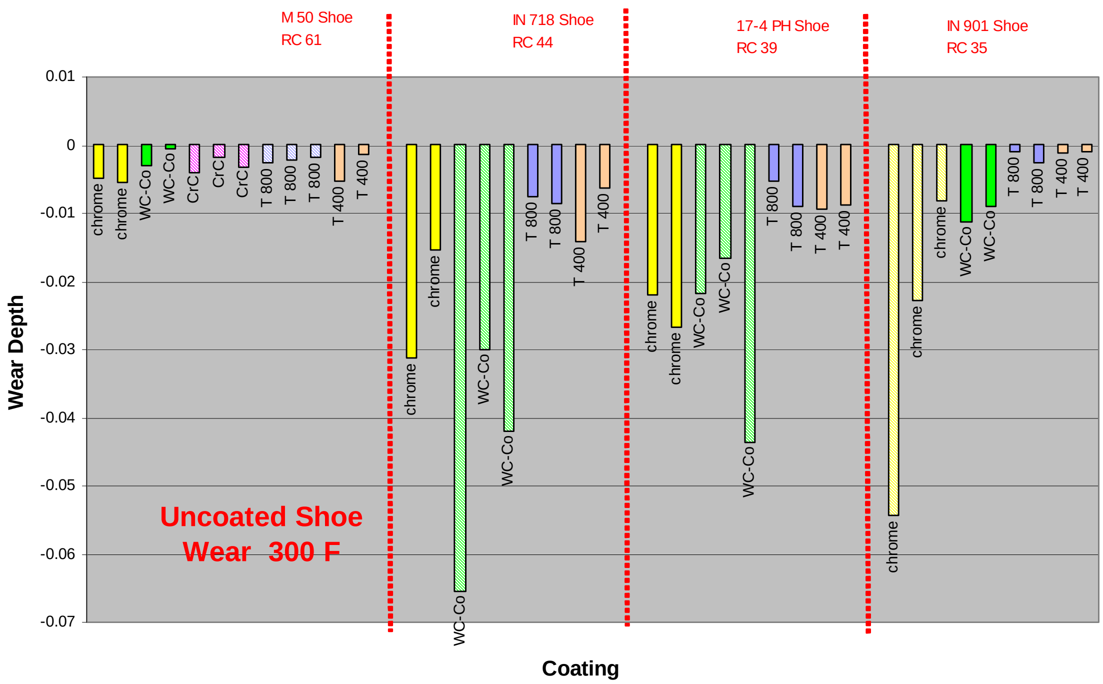

Figure 14. Wear Coefficients (plotted as average wear depth**) for Shoes Sliding Against the Indicated Coatings for Testing at 300ºF.**

5.2.3 Materials Testing—Corrosion

Figure 15 is a summary of the protection ratings that were determined for the coated 4340 steel rods after 1000 hours of B117 salt fog exposure. The 0.003 in-thick EHC coatings outperformed the 0.003-in-thick HVOF and APS coatings in every direct comparison. There was blistering and cracking of all of the 0.003-in-thick HVOF and APS coatings. For the 0.015-in-thick coatings, the HVOF T-400 and APS T-400 provided significant protection to the 4340, essentially equivalent to the EHC (with or without the Ni underlayer). However, the 0.015-in-thick HVOF Cr_3C_2/NiCr and HVOF T-800 did not provide protection equivalent to that of the EHC.

The relative performance of all the coatings on the 4340 plates was very similar to that on the 4340 rods. On both the rods and plates, in many cases the epoxy mask failed and crevice corrosion was occurring underneath the epoxy. The crevice corrosion was observed on virtually all the HVOF and APS coatings and on a few of the EHC coatings. (Note, however, that this was not a true crevice corrosion test, and results in such a test may be very different.) There was a definite substrate effect in that the protection ratings for all of the 0.003-in-thick and 0.015-in-thick coatings on the IN-718 substrates was greater than 7, with very little corrosion noted and none of the blistering or cracking that was observed on HVOF or APS coatings on the 4340 substrates.

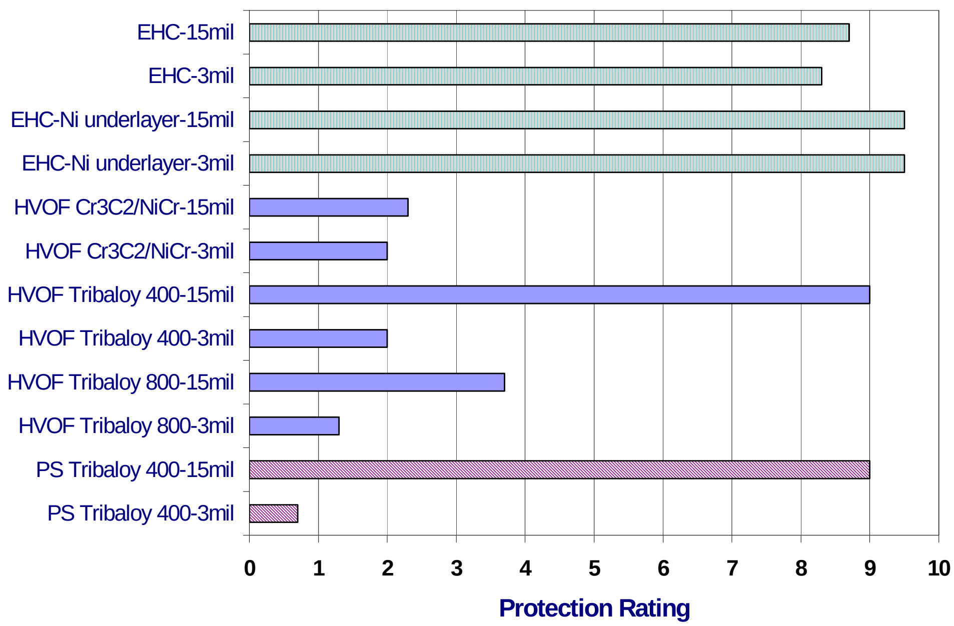

Figure 15. Protection Ratings for Coated 4340 Steel Rods After 1,000 Hours of Salt Fog Exposure.

5.2.4 Materials Testing—Carbon Seal

Because the load being applied between the coated rotor and the carbon seal was not absolutely constant as it was applied with a typical engine spring arrangement, the wear depths measured on the carbon seals and coatings for each test were normalized by dividing by both the time to complete the test and the surface interface pressure as calculated based on the load and contact area. The normalized value was then designated the wear coefficient or factor, K. The baseline value for carbon seal wear was considered to be the lowest value obtained for sliding against EHC. Then K-ratios were plotted in which the wear of the carbon seal sliding against the coating under consideration was divided by the baseline value. An example of the results obtained is Figure 16, which shows the K-ratios for the wear of the Graphitar 39 carbon seal sliding against different coatings for a test performed at 13,500 rpm. With respect to the EHC alone, it can be seen that the wear of the carbon seal was greatly reduced by using an Ra surface finish of 4 microinches on the EHC. The only thermal spray coating that was superior to the optimum EHC was HVOF WC/17Co, with the others having wear coefficients on the carbon seals that were factors of 2 to 7 higher. However, if a comparison is made on the basis of equivalent surface finish, then all the thermal spray coatings with an Ra surface finish of 8 microinches were superior to the EHC coating with the 8-microinch surface finish. Measurements taken on the coatings themselves indicated that the wear of the HVOF WC/Co coatings was equivalent to that of EHC, with the wear rates on the other thermal spray coatings somewhat higher.

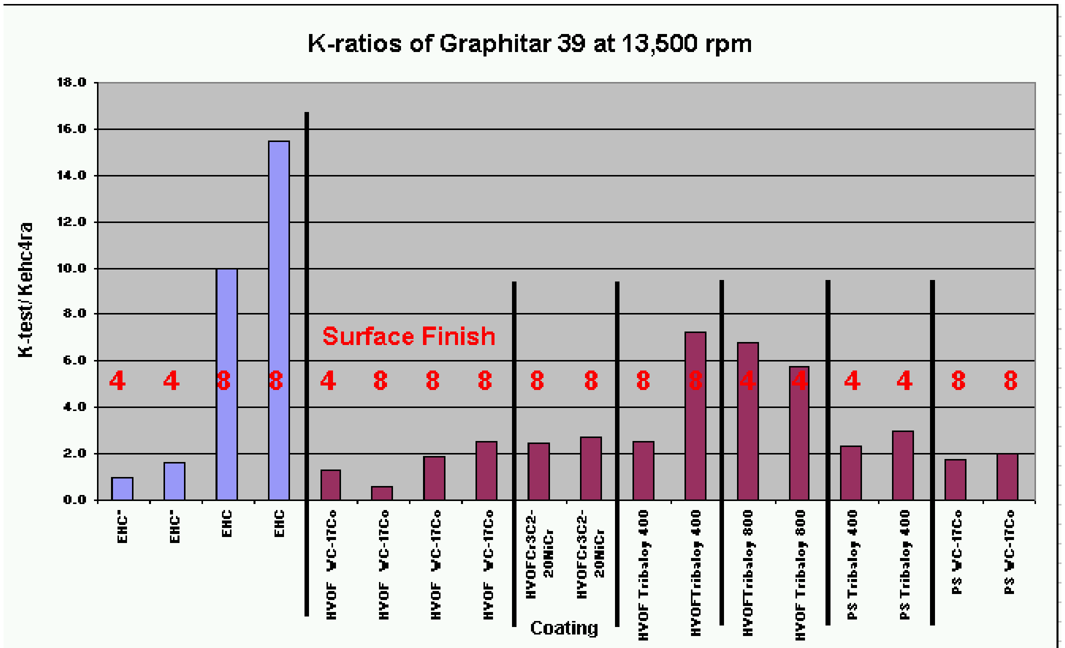

Figure 16. Ratio of Wear Coefficients for Indicated Coatings to Optimum EHC Coating for Sliding Against Graphitar 39 Carbon Seals at 13,500 rpm.

There are more than 3000 TF33 gas turbine engines in service throughout the Air Force on the B-52H, C-141, E-3, and KC-135 aircraft, and repair of components from this engine represents the largest chrome plating workload at OC-ALC. Therefore, testing of selected HVOF-coated components that are normally EHC-plated in a TF33 engine test was viewed as a high priority and essential to move toward qualification of the HVOF coatings. Process and materials engineers from OC-ALC and P&W identified the engine part classes that were high-volume HVOF repair candidates, then participated selecting components to be coated and tested in a TF33 AMT engine. They were the Low Pressure Turbine Shaft, High Pressure Turbine Shaft, #1, #5, #6 Bearing Housings, Rear Compressor Rear Hub, and Front Compressor Rear Hub. Based on their operating temperatures and previous P&W experience, it was decided that WC/17Co coatings would be applied onto the components. Figure 17 shows a cross section of the TF33 engine indicating the locations of the seven selected components.

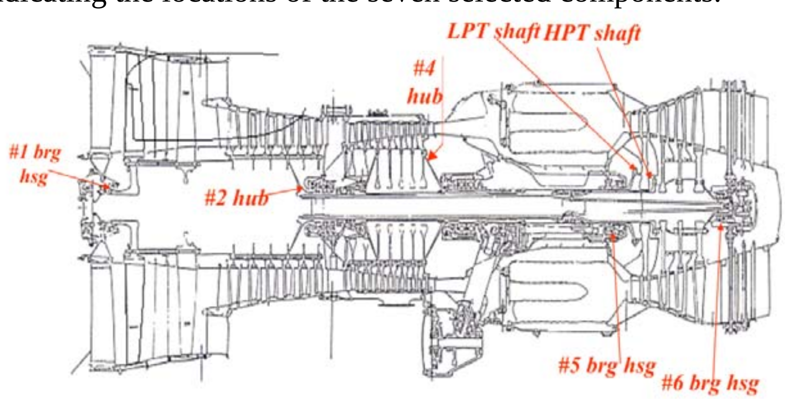

Figure 17. Cross-Section Schematic of TF33 Engine Showing Location of Components onto Which the HVOF WC/Co Coatings Were Applied.

There were two complete sets of components processed with HVOF WC/Co coatings by Engelhard Corporation following P&W specification PWA 36206-1. The first set was designated the functional test components, and the second was designated the operational test components. The functional tests were performed at the Air Force Phoenix Air National Guard (ANG) Engine Shop and consisted of pressing bearings onto and into the HVOF coated components five times. The coatings were then visually examined and showed no evidence of chipping, flaking or cracking. Then the components were returned to P&W for fluorescent penetrant inspection (FPI), which did not indicate coating cracks or other defects. Finally, the components were cut up and metallurgical analyses were performed on cross sections of the coatings, which found that they were all acceptable in terms of oxide content, porosity, interfacial contamination, carbide content, and internal defects.

Following analysis of the functional components, the operational test components were shipped to the Air Force Phoenix ANG engine shop where they were assembled into the AMT engine. The endurance portion of the AMT began on October 30, 2001 and the engine ran for 4,500 equivalent flight hours (EFH). On completion of the test, the engine was disassembled, and a visual inspection of the components indicated no visible damage. The components were then shipped to P&W in East Hartford, Connecticut, for FPI (both standard and ultra-high sensitivity [UHS]) and destructive evaluations. Of the seven TF33 components evaluated, many with multiple coated surfaces, only two components displayed indications under either standard or UHS FPI. Very small cracks were evident near the edge of a coating on the #2 bearing journal, and there was some evidence of carbide pullout. A very small crack-like indication was also present on the #5 bearing journal. In each case, the indications were not significant enough to cause rejection of the coating for continued service. Virtually no dimensional changes were observed on the any of the components. Metallographic examinations were performed on three of the tested components, (1) #6 Bearing Housing, (2) #2 Front Compressor Rear Hub, and (3) Rear Compressor Drive Turbine Shaft. For (1) and (3), the HVOF coatings were found to be in excellent condition. For (2), there was some evidence of coating loss but not sufficient to cause rejection of the part.

There was a concern that coating particulates could get into the oil system and result in bearing compartment wear if the HVOF coating were to spall or wear. Therefore, the AMT incorporated filter debris and oil analysis to examine for the presence of either tungsten or cobalt. At every 476 EFH, the main oil filter was removed and analyzed. Oil samples were periodically removed from the engine and were analyzed using inductively coupled plasma mass spectrometry. There were no detectable indications of tungsten or cobalt in any of the oil samples. Small, fine-grained pieces of tungsten and cobalt were detected in oil filters from the latter stages of the AMT, but the concentration was very low and was not considered significant.

5.3 DATA EVALUATION

Fatigue

Fatigue was established as the most important materials property for qualification of the thermal spray coatings as a replacement for EHC on the various alloys used in GTEs. For most substrate/coating combinations, the fatigue performance of the thermal-spray-coated samples was at least equivalent and usually superior to the performance of the EHC-coated samples. Clearly, the primary fatigue problems are with IN-718, especially at 750ºF (where half the WC-

Co and Cr3C2-NiCr data fell below the baseline) and 17-4PH (where almost 40% of the 750ºF data fell below the baseline). It is not clear why these materials should show a larger debit. Their hardness, elastic moduli, and coefficients of thermal expansion are similar to the other alloys, and they do not appear to be particularly heat-sensitive and therefore more strongly affected by the spray temperature. There are a great many factors that influence fatigue crack initiation, and it is not possible to understand why these coated materials are more fatigue-sensitive without extensive materials analysis, which was beyond the scope of this project.

It is known, however, that fatigue may be strongly affected by deposition conditions. The deposition conditions used for coating IN-718 and 17-4PH, as for coating all the other alloys, were determined by optimizing for fatigue of coated 4340 steel. However, it may well be that these alloys demand somewhat different deposition parameters for optimized fatigue. That this may be the case is shown by data obtained under a separate project in 1997 for HVOF WC/Co on IN-718 at 800ºF [3]. Both HVOF WC/Co and T-400 were optimized for deposition on IN-718 by a full DOE. While the fatigue curve for the T-400 was well above that of the hard chrome baseline, the curve for WC/Co was only a little above the EHC and, in fact, appeared to fall a little below it at the highest stress. Although no prior data are available for 17-4PH, early data on 13-8Mo (another precipitation hardened stainless steel) showed very similar fatigue debits for HVOF carbide and EHC coatings. Therefore, if carbides are to be used on IN-718 or 17-4PH the deposition parameters must be properly optimized for those alloys through a DOE analysis, with careful quality control to ensure their reproducibility.

Wear

In analyzing the wear results, it was essential to examine not only the wear of the coatings but also the total system wear, which included the wear on the mating materials. The fact that the wear for the majority of the coated blocks extended beyond the 0.003-in coating thickness, with total wear ranging up to 0.021 in at 300ºF and up to 0.035 in at 750ºF, makes quantitative comparisons difficult. However, there are some conclusions that can be inferred from the results. More definitive conclusions can be drawn from the results at 750ºF than from the results at 300ºF. At the higher temperature, WC/Co performed significantly better than hard chrome and the other thermal spray coatings for all mating materials except for the IN-718 shoes where the performance was comparable to hard chrome. This was the case for both coating wear and total system wear. The results for testing at 300ºF were less definitive. For sliding against M50, WC/Co is the superior coating, with slightly lower coating and total system wear rates. The other thermal spray coating wear rates were substantially higher. For sliding against IN-718, the wear rates for the WC/Co were very low, but the mating surface wear was exceptionally high, making total system performance lower than for hard chrome. In this case, HVOF T-800 or APS T-400 provides total system wear performance comparable to hard chrome. For sliding against 17-4PH, total system performance for any of the thermal spray coatings is essentially comparable to hard chrome. Finally, for sliding against IN-901, the WC/Co coatings provide substantially lower coating and mating surface wear rates than for hard chrome. Overall, out of the eight combinations of mating surface and temperature, WC/Co is the clear choice for six, with HVOF T-800 or APS T-400 the choice for lower temperature sliding against IN-718 and 17-4PH.

Corrosion
The results from the B117 salt fog corrosion tests indicated that the performance of all of the 0.003-in-thick thermal spray coatings was inferior to that of the 0.003-in-thick EHC coatings on 4340 steel rods and plates. These results are similar to those obtained for WC/Co coatings on 4340 in the landing gear project [5] where the performance of EHC was superior. However, in that case, atmospheric corrosion testing and in-service testing showed that the performance of the WC/Co coatings was superior to EHC. Thus, there continues to be controversy about the validity of the B117 test in correctly predicting real-life performance of coated steel alloys. It is interesting to note that the performance of the thermal spray coatings was significantly better on the IN-718 substrates, indicating that the coatings do not provide complete barrier protection and thus the performance of the entire coating/substrate combination must be taken into account.

Carbon Seal
The results of the carbon seal testing were not entirely definitive. The individual from GE Aircraft Engines who coordinated these tests and specified the surface finishes could not explain the wide disparity in wear of the carbon seal materials between using a surface finish of 4 microinches versus 8 microinches on the EHC coatings. He indicated that a surface finish of 8 microinches is most commonly used, and that is why most of the thermal spray coatings had a finish of 8. It is not known why the carbon seals were more sensitive to surface finish for the chrome than for the thermal spray coatings, and addressing the issue definitively would require additional testing that was not possible in this project. The best way to interpret the data was to make a comparison between the coatings at the same level of surface finish, and from that it was clear that the wear of the carbon seal materials sliding against HVOF WC/Co was at least equivalent to the wear sliding against EHC at either level of surface finish; therefore, WC/Co is an acceptable alternative.

Component Test
As a result of the successful TF33 AMT engine test, the seven HVOF WC/Co-coated components will be installed in another AMT to determine if they can survive up to 9000 EFH. In almost all circumstances, had EHC been used on these components, they would have required overhauling at 4500 EFH by stripping and re-applying the EHC. Therefore, it appears that the HVOF WC/Co coatings will be able to remain in service through more than one overhaul cycle, thereby reducing life-cycle costs.

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6.0 COST ASSESSMENT

6.1 COST REPORTING

A detailed cost/benefit analysis (CBA) for replacement of EHC plating with HVOF thermal spray was conducted at a facility that performs repair and overhaul of military gas turbine engines [8]. Data collection at the facility and financial analyses of the data were performed using the JG-PP Environmental Cost Analysis Methodology (ECAM) [9]. Hard chrome is applied to turbine engine components to restore dimensions on worn or repaired parts. Although it depends on the depth of the wear or the amount of material required to restore dimensional tolerances, on average a 0.015-in-thick coating is deposited, which is then machined down to a thickness of approximately 0.010 in. The current chrome plating process at the repair depot includes five chrome plating tanks and two rinse tanks. To prepare parts for plating, several other activities are also performed, including stripping, shot peening, blasting, and masking. Masking typically consists of using lead tape and plating wax. Postprocessing steps include demasking, cleaning (using a perchloroethylene degreaser), baking, grinding, and inspection. Specific activities, their frequency and sequence, vary depending in part on geometry, condition, and other parameters. The baseline process flow diagram for the current hard chrome electroplating process at the depot is provided in Figure 18.

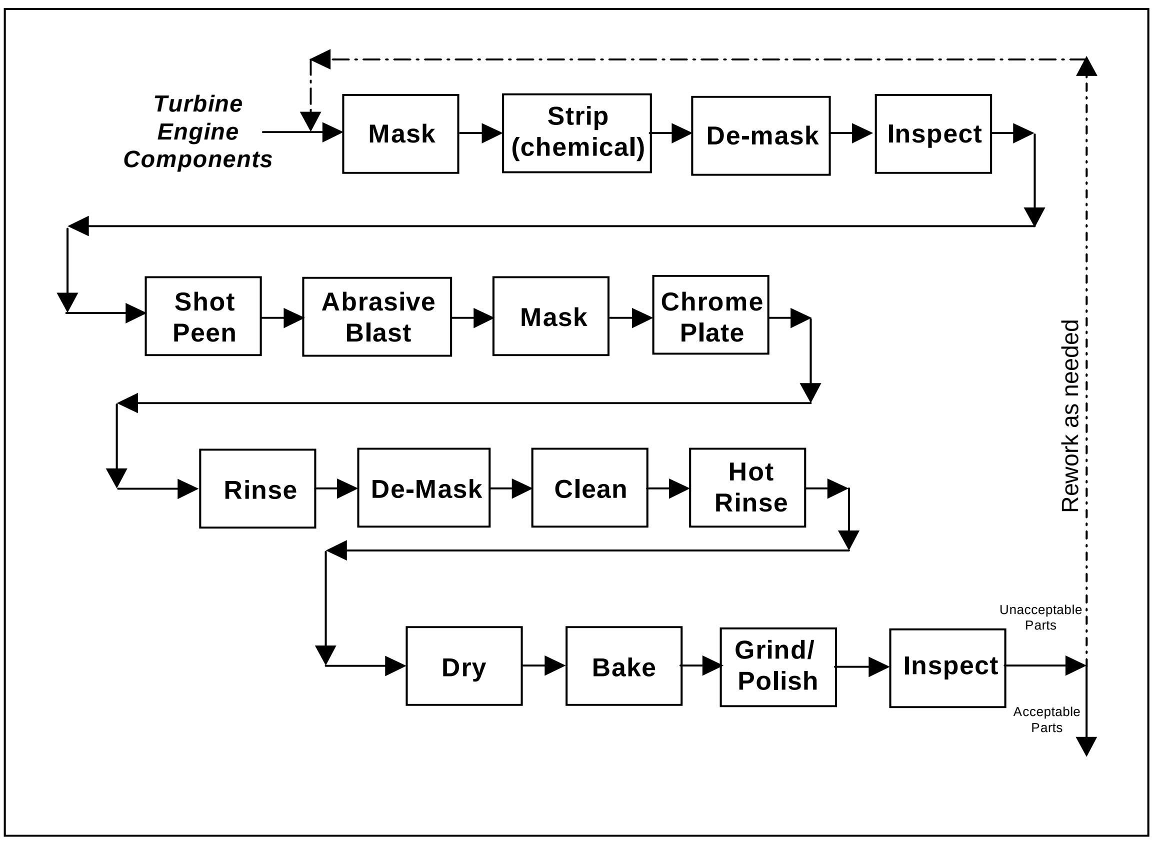

Figure 18. Process Flow of Hard Chrome Plating at the Military Gas Turbine Engine Repair Depot.

A site visit was performed on March 4-7, 2002, to collect baseline data on the hard chrome plating process at the repair depot. During the site visit, interviews were held with process engineers, plating operators, plating supervisors, turbine engine program managers, environmental staff, and other employees throughout the facility. The information gathered during the site visit was supplemented with additional correspondence following the visit.

The CBA was performed only for replacement of EHC plating on the components from one engine, which makes up the majority of the plating performed at the depot. The annual throughput of components from this engine at the depot was 678 in FY 2001, with a total surface area of 225 square ft being plated. The types of components included bearing housings, hubs and turbine shafts.

The following engineering assumptions were used in evaluating the baseline hard chrome plating process:

- Transition of selected engine components to HVOF will result in the depot shutting down two of five plating tanks and one of two rinse tanks. Therefore, utility costs for the affected components are based on the operation of two plating tanks and one rinse tank.
- The chrome plating shop is operated 50 weeks per year.
- The rework rate for chrome plating is 10%.
- Chrome plating tank concentrations are tested weekly at a cost of $640/week.
- The cost to manage perchloroethylene emissions and waste is approximately nine times the material cost of perchloroethylene.
- Approximately 500 labor hours are required for the management of chrome plating waste associated with affected TF33 components.
- The labor rate used in this analysis is $65 per hour; which is considered a fully-burdened rate and is often used as a default rate for DoD CBAs.

The annual operating costs for EHC plating of the components from the engine under consideration were determined to be $150,000, of which approximately $128,000 was for labor, $7,000 for materials, $10,000 for utilities, and $5,000 for waste disposal.

A process flow diagram of the application of WC/Co by HVOF thermal spraying was developed to aid in the collection of data for the HVOF process alternative. A generic process flow diagram for HVOF is shown in Figure 19. Note that five process steps, other than the plating (coating application) step, are expected to be eliminated when transitioning from hard chrome electroplating to HVOF thermal spraying—Rinse, Clean, Hot Rinse, Dry, and Bake. In addition, the masking required for HVOF consists of tape and hard fixturing, as opposed to the lead tape and wax dip process used for hard chrome plating.

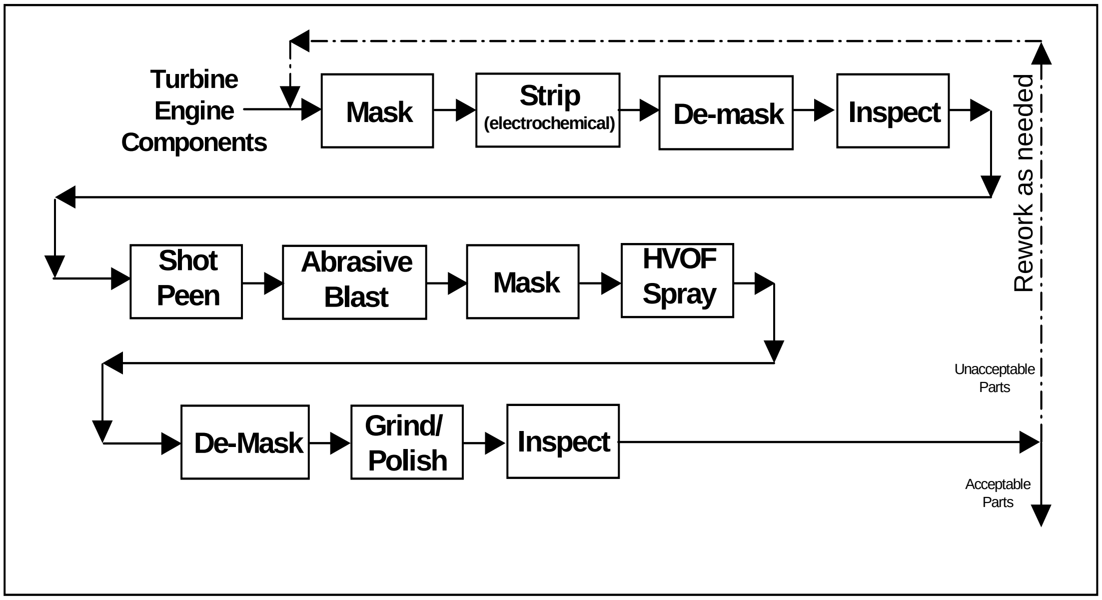

Figure 19. Projected Process Flow for HVOF Thermal Spraying at the Military Gas Turbine Engine Repair Depot.

The following engineering assumptions were used in evaluating the HVOF thermal spray coating process:

- Approximately 47% of the parts currently chrome plated will be transitioned to HVOF.
- All operating parameters are based on Sultzer Metco specifications for a Diamond Jet DJ2600 system.
- WC/Co is deposited to a thickness of 0.015 in and ground down to a final thickness of 0.010 in, as is presently done with the current chromium coating.
- The rework rate for HVOF thermal spray is 5%.
- The HVOF spray process has a 40% (deposited to sprayed) coating efficiency.
- Hydrogen (H_2) gas will be used as the fuel gas.
- HEPA filters in the dust collection system will be replaced every 5 years at a cost of $20,000, plus $250 for disposal of spent filters.
- The cost of WC/Co powder coating is $32 per lb.
- Initially (in the first few months), all components (up to 10% of annual throughput) will have a sample coupon coated and sent to the lab for testing to assure that the process is operating within specifications.
- Upon obtaining a controlled spray process, a sample coupon will be coated and tested once per month.

- Lab cost to perform QA/QC test on coated panel is $350 per panel.
- To assure compliance with specifications, the depot will test all WC/Co powder lots to verify composition at a cost of $150 per lot.
- Water and electricity usage is based on 125% of the hourly use of HVOF thermal spray equipment.
- The air filtration system operates 40 hours/week, 50 weeks/year.
- Ventilation electricity costs are based on a 15 hp (11.19 kW) motor in the air filtration system.
- The ratio of labor for masking (HVOF versus hard chrome) is 1:1.
- The ratio of labor for coating (HVOF versus hard chrome) is 1.5:1.
- The ratio of labor for demasking/cleaning (HVOF versus hard chrome) is 0.27:1.
- The ratio of labor for grinding (HVOF versus hard chrome) is 0.75:1.
- The cost of stripping chrome is comparable to the cost of stripping HVOF.
- Maintenance to clean spray booths is performed quarterly, 8 hours per booth.
- Maintenance to clean hard masking fixtures is performed monthly, 6 hours per booth.
- The cost of waste disposal for HVOF overspray and filters is $0.25 per pound.

Related to capital costs, the repair depot has already installed one HVOF spray booth, which consisted of the purchase of a robot, turntable, controller, feeder, and the retrofit of an existing spray booth and dust collection system. The new equipment cost $200,000, and an additional $275,000 will be spent to move and reinstall the dust collection system and make necessary safety modifications. The purchase of an additional HVOF thermal spray system is anticipated to cost $500,000. Thus, the total capital equipment cost is estimated at $975,000. However, for the purposes of this analysis, only one booth at $500,000 was input as a capital investment since it is sufficient to handle the throughput of the specific engine components. In addition to the initial equipment costs, the costs of initially testing sample coupons to ensure process quality control (approximately 10% of the annual throughput of the engine components) and the cost of training personnel to operate the HVOF system were considered. It was estimated that the cost of the testing and training would total $38,368.

6.2 COST ANALYSIS

The data and assumptions described in Section 6.1 were used to estimate the costs associated with applying HVOF WC/Co coatings onto the specific engine components in place of EHC. Case 1 assumed that there would be a constant throughput of the 678 components over the 15-year analysis period. The total annual operating cost for using HVOF in this case was $99,866. Case 2 assumed an extension in service life that HVOF is expected to provide; therefore, components previously coated with HVOF that return to the depot may not necessarily have to be processed but can be returned to service. The following assumptions were used to analyze the costs under this Case 2 scenario:

- *Years 1-5.* All engine components coming into the depot have chrome plating that is stripped for inspection and repair purposes. Applicable components are recoated using HVOF thermal spray at the current throughput rate of 678 parts per year.
- *Years 6-10.* 50% of the specific engine components processed are chrome-plated parts, which are stripped, inspected, repaired, and recoated using HVOF thermal spray. It is assumed that the remaining 50% of the parts were previously coated using HVOF. It is estimated that 50% of these components (25% of the total throughput) will be stripped, inspected/repaired, and recoated using HVOF. The remaining components (25% of the total throughput) will require no processing. Thus, the total number of parts processed annually will be 424 components.
- *Years 11-15.* All specific engine components coming into the depot were previously coated using HVOF. Of these, 25% will be stripped, inspected/repaired, and recoated using HVOF thermal spray. The total number of parts processed annually will be 170 components.

Based on the above assumptions, the annual operating costs for Case 2 for HVOF in years 1-5, 6-10, and 11-15 were calculated to be $99,866, $65,406, and $31,083, respectively.

A third case analysis was also performed to consider the additional savings that could be attributed to HVOF thermal spray if hard chrome plating was completely eliminated at the repair depot. Until chrome plating is completely eliminated, permitting, record keeping, training, and other management costs associated with the use of hexavalent chromium are not likely to change. However, assuming that the depot does eliminate the hard chrome plating process through implementation of alternative technologies, an additional $150,000 environmental management burden will be avoided. Of that cost avoidance, $70,500 can be attributed to the transition of candidate components from the specific engine considered to HVOF thermal spray. Assuming the same operating costs for declining component throughput as Case 2, a cost benefit analysis factoring in this additional cost avoidance (accounted for as an additional environmental management burden on the baseline hard chrome plating process) was performed as Case 3.

To measure the financial viability of this project, three performance measures for investment opportunities were used: net present value (NPV), internal rate of return (IRR), and payback period. The NPV is the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. The IRR is the discount rate at which NPV is equal to zero. NPV and IRR account for the time value of money and discount the future capital investments or annual cost benefits to the current year. For NPV and IRR, a 3.5% discount rate was used for this financial evaluation. The payback period is the time period required to recover all the capital investment with future cost savings. A summary of the financial evaluation for implementing HVOF to replace hard chrome electroplating on components from the selected engine is shown in Table 8, Table 9, and Table 10 for Cases 1, 2, and 3, respectively. This financial evaluation includes the annual operating costs and initial investment costs discussed above.

Table 8. Results of Financial Evaluation for Constant Throughput—Case 1.

Financial Indicator	5-yr	10-yr	15-yr
Net Present Value	($327,688)	($150,301)	$11,142
Internal Rate of Return	NA	NA	3.8%
Discounted Payback	14.6 years		

Table 9. Results of Financial Evaluation for Declining Throughput—Case 2.

Financial Indicator	5-yr	10-yr	15-yr
Net Present Value	($327,688)	($19,299)	$362,304
Internal Rate of Return	NA	NA	10.2%
Discounted Payback	10.2 years		

Table 10. Results of Financial Evaluation Accounting for Additional Cost Avoidance Realized with the Total Elimination of Chromium Plating—Case 3.

Financial Indicator	5-yr	10-yr	15-yr
Net Present Value	($9,377)	$567,022	$1,174,282
Internal Rate of Return	2.9%	19.9%	23.6%
Discounted Payback	5.1 years		

The above analysis did not take into account the lowering of the hex-Cr PEL because, at the time of performing the initial analysis, OSHA had not issued any new standards. However, in late 2004 OSHA proposed a new standard for occupational exposure to hex-Cr in response to evidence that occupational exposure poses a significant risk of lung cancer and nasal septum ulcerations. To protect exposed workers from these effects, OSHA has proposed a PEL of 1 microgram-per-cubic-meter measured as an 8-hour time weighted average. If this new PEL is finalized, it is expected that additional measures will need to be taken by the facility to meet these regulations. Therefore, to ensure a complete analysis, a scenario was created where the baseline hard chrome plating continues to be used after the new regulations come into effect. This increased cost of using the baseline process was compared to the HVOF process.

Due to the difficulties associated with predicting the economic impact of a proposed regulation, a Monte Carlo simulation was used. Expected cost factors provided by OSHA were used to forecast the potential impact resulting from the proposed new PEL. Based on their report, it was assumed that the annual operating costs could increase from between $14,000 to more than $50,000. The Monte Carlo simulation, using the recent cost expectations published by OSHA, indicated a mean 15-year NPV to range from $350,000 for a constant throughput to $701,400 for a declining throughput to $2.9 million if all chrome plating operations were eliminated. Therefore, as expected, the cost savings associated with transitioning to HVOF are greatly increased if the new PEL is implemented.

7.0 IMPLEMENTATION ISSUES

7.1 COST OBSERVATIONS

A cost benefit analysis was performed to identify the potential financial impact of implementing the HVOF coating process at a military gas turbine engine repair facility for application to the components from the engine that provided the largest chrome plating workload. Data were collected at this facility and the potential economic effects were calculated in accordance with the ECAM. It was estimated that the use of HVOF on the turbine engine components would result in a net decrease in annual operating costs at the depot of approximately $50K. At this rate, it would take more than 14 years to pay back the capital investment costs of implementing HVOF. Additional savings will be realized if the requirement to strip HVOF for component inspection is waived based on the increased service life that HVOF is anticipated to provide. In this case, the number of parts processed will decrease over time once all chrome-plated parts have been coated with HVOF WC/Co. For this scenario, the potential savings (NPV) over 15 years is over $362K with a payback period of just over 10 years. Further cost savings (through reduced environmental management burden) will be realized and should be attributed to the HVOF thermal spray process once the depot completely eliminates all hard chrome plating operations. Considering this additional cost benefit, the potential savings are greater than $1 million over the 15-year study period, and the payback period is just over 5 years.

It should also be mentioned that the CBA described in Section 6.0 did not take into account any increases in EHC plating costs resulting from more stringent worker safety regulations such as the anticipated significant reduction in the hex-Cr PEL. This was because engineers at the depot believed they were already capable of meeting the new levels. However, most military repair depots are not currently capable of meeting the anticipated new PELs, so their cost would increase substantially and that would have to be taken into account in any CBAs performed at those facilities.

7.2 PERFORMANCE OBSERVATIONS

In general, the fatigue performance of A-286, AMS-355, 9310, IN-901, and 4340 alloy samples coated with the thermal spray coatings was equivalent to or exceeded that of equivalent samples coated with EHC. However, for approximately 50% of the IN-718 and 40% of the 17-4PH samples, the fatigue performance of the thermal spray coatings was inferior to that of EHC. The reason for this could not be determined without further study, but based on earlier results as discussed in Section 5.3, it is anticipated that by further optimization of coating deposition parameters for high temperature fatigue, the fatigue performance can be improved to at least match that of EHC. Because of the successful rig test on IN718 TF33 components, HVOF WC/Co coatings are being implemented on those types of components regardless of the fatigue results on IN718. For fretting wear tests conducted at 750º F, HVOF WC/Co coatings performed significantly better than EHC and the other thermal spray coatings when sliding against all of the mating materials, except IN-718 where the coating performance was equivalent to EHC. For fretting wear tests conducted at 300ºF, the results were less definitive but in most cases, WC/Co performance was equivalent or superior to EHC. In B117 salt fog corrosion testing, the performance all of the 0.003-in-thick thermal spray coatings was inferior to EHC whereas the performance of the 0.015-in-thick thermal spray coatings was generally equivalent to EHC on

4340 steel substrates. For all coatings on IN-718, very little corrosion was observed at either thickness. For the carbon seal tests, in general the performance of the HVOF WC/Co coatings was equivalent to EHC in terms of both the wear of the coating and the mating carbon seal material.

Coating integrity can be defined as the ability of a coating to continue protecting the underlying material during application of cyclic stresses without significant cracking (which may cause a corrosive medium to penetrate to the substrate) and without delamination or spalling, which clearly would result in a loss of protection. This was an issue in the landing gear project where delamination of HVOF WC/Co coatings was observed under certain fatigue test conditions involving high levels of alternating stress [5]. For the GTE project, the levels of alternating stress or strain were generally less than in the landing gear project, therefore, delamination during the running of the tests was not encountered. Delamination was observed, however, after failure of the fatigue specimen, with the coating spalling in the vicinity of the fracture. Significant cracking of any of the thermal spray coatings during fatigue testing was rare. On a few samples with 0.015-in-thick WC/Co coatings undergoing LCF testing, circumferential or ring cracking was observed, presumably because the stress ratio was greater for LCF than for HCF testing. As was observed in the materials tests for the landing gear project [5], there is a greater potential for cracking of the coatings as the stress ratio is increased. However, the presence of cracks does not mean that the coatings would be rejected in service (consider the extensive cracking in EHC coatings) as long as delamination is not observed.

7.3 SCALE-UP ISSUES

Both OC-ALC and NADEP-JAX have two full production HVOF thermal spray systems with fixturing for manipulation of various types of gas turbine engine components and seven-axis robots on which the HVOF spray guns are mounted. Procedures have been developed for processing various types of GTE components such as the TF33 components that were qualified in the AMT. This includes mounting of appropriate masks on either the fixtures or the components to ensure coating application only in designated areas. Grinding procedures for the coatings to ensure proper surface finish have also been developed. Therefore, there are no scale-up issues associated with implementation of the thermal spray technology.

7.4 OTHER SIGNIFICANT OBSERVATIONS

The success of the materials testing and the TF33 AMT has resulted in the Air Force proceeding with implementation of HVOF coatings on other gas turbine engines through the Component Improvement Program, with the ultimate goal of eliminating hard chrome plating on all components for which thermal spray is amenable (i.e., where line-of-sight is not an issue). This includes repair of the F100, F101, F110, F118, and T56 engines. In addition, Chromalloy, a contractor that overhauls the TF39 for the Air Force, is moving towards implementation of HVOF at its San Antonio repair facility. Their analysis shows a very significant reduction in turnaround time for HVOF repair.

The Process Engineering Department at OC-ALC has established a quality control methodology that includes the development of a process order to control thermal spray application procedures and acceptance criteria based on analysis of test coupons prior to initiating thermal spray runs. A special skill qualification program has been established to certify thermal spray operators.

7.5 LESSONS LEARNED

In attempting to qualify and implement a new technology on safety-of-flight components such as rotating parts on GTEs, it is essential to involve the entire stakeholder community from the outset and identify important areas of concern. Contributions from program offices, system support offices, depot engineers, and OEMs were made toward development of the JTP and all results, positive and negative, were presented to them for evaluation and consideration. When an unexpected issue arose, it was again important to involve the stakeholder community and obtain their criteria for acceptable performance. There must be flexibility (both programmatic and financial) built into any project of this type so that unplanned testing can be conducted to address unforeseen issues.

7.6 END-USER/OEM ISSUES

One of the key end-user/OEM issues is the availability of standards and specifications related to the powder used for HVOF coatings, application procedures for the coatings, and grinding procedures for the coatings. The HCAT has worked with the SAE Aerospace Metals Engineering Committee to develop four separate specifications in these areas. Those related to powder, coating deposition and grinding were completed and forwarded to SAE Aerospace Materials Committee B. The following are the designations:

AMS 2448 – "Application of Tungsten Carbide Coatings on Ultra-High-Strength Steels, High-Velocity Oxygen/Fuel Process," issued in August 2004

AMS 2449 – "Grinding and Superfinishing of Tungsten Carbide Coatings Deposited Using High-Velocity Oxygen/Fuel Process," issued in August 2004

AMS 7881 – "Tungsten Carbide-Cobalt Powder, Agglomerated and Sintered," issued in April 2003

AMS 7882 – "Tungsten Carbide-Cobalt Chromium Powder, Agglomerated and Sintered," issued in April 2003

Although AMS 2448 was developed principally for landing gear, the procedures are applicable to other components such as gas turbine engines. In fact, the parameters defined in AMS 2448 were used for application of WC/Co on the GTE materials specimens. All these specifications can now be utilized by any manufacturing or overhaul depot, and their use will result in consistency between facilities with respect to coating properties.

If other coatings that were evaluated in the GTE materials testing are intended to be used, then additional specifications will have to be developed. This was beyond the scope of this project.

7.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The principal environmental and worker safety issues associated with HVOF thermal spraying are air emissions containing overspray particles and the noise of the gun itself. All the depots involved in the HCAT project already had other types of thermal spray equipment in operation, such as flame or plasma spray, and therefore had the appropriate air handling equipment (e.g., exhaust hoods, bag houses) available and also had the appropriate air permits to cover operation of the HVOF systems. With respect to noise, all of the HVOF systems are installed in soundproof booths and are computer-controlled. Therefore, no operator is exposed to the noise of the HVOF gun.

8.0 REFERENCES

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3. "Hard Chrome Coatings: Advanced Technology for Waste Elimination," Final Report issued by Northwestern University, Evanston, IL, under DARPA Contract MDA972-93-1-0006, 1996

4. "Materials Joint Test Protocol, Validation of Advanced Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Gas Turbine Engines," Prepared by Hard Chrome Alternatives Team for Environmental Security Technology Certification Program, 30 September 2001.

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9. "Environmental Cost Analysis Methodology (ECAM) Handbook." Environmental Security Technology Certification Program Validation Tasks. Contract No. DAAA21-93-C-0046. Task No. 098, CDRL No. A013. Concurrent Technologies Corporation. March 1999.

APPENDIX A

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